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DEFENCE DÉFENSE

High Frequency Target Strength Predictions

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Martec Technical Report: TR-06-17

Contract Number: W7707-05-3160/A

Contract Scientific Authority: Layton Gilroy, 902-426-3100 x365

Defence R&D Canada – Atlantic

Contract Report
DRDC Atlantic CR 2007-043
February 2007

Canada

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Scientific Authority

Layton Gilroy

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Abstract

This report describes the contract addressing the need to extend the current capabilities of DRDC's AVAST software in order to provide a modelling tool suitable for predicting radiated noise and target strength of realistic ship structures. In this work, the contractor developed, as input, high fidelity models of both the Canadian Patrol Frigate and CFAV Quest. For the purpose of acoustic target strength prediction, these models included sufficient detail to allow for predictions at 50 kHz. In terms of radiated noise, the contractor developed a methodology for predicting hull surface accelerations, internal structural vibrations, and internal compartment radiated noise (up to approximately 50 Hz) due to an idealized acoustic source simulating propeller cavitation. The contractor investigated discrepancies between the Kirchhoff and conventional BIEM formulations when used for predicting torpedo target strength. In addition, the contractor provided a capability for including a nominal propeller model when predicting the medium-to-high-frequency target strength of a submarine or torpedo.

Résumé

Le présent rapport décrit le contrat portant sur l'amélioration du logiciel AVAST de RDDC afin d'en faire un outil plus adéquat pour la prévision du bruit rayonné et de l'indice de réflexion de structures de navires réalistes. Dans le cadre de ses travaux, l'entrepreneur a mis au point, à titre de données d'entrée, des modèles de grande qualité à la fois de la Frégate canadienne de patrouille et du Navire auxiliaire des Forces canadiennes Quest. Aux fins de la prévision de l'indice de réflexion acoustique, ces modèles comprennent suffisamment de détails pour permettre des prévisions à 50 kHz. En ce qui a trait au bruit rayonné, l'entrepreneur a mis au point une méthode visant à prévoir le bruit rayonné par les compartiments internes (jusqu'à environ 50 Hz) dû à une source acoustique théorique simulant une hélice en régime de cavitation. L'entrepreneur a examiné les écarts entre la méthode de Kirchhoff et la méthode des équations intégrales de frontière classiques dans la prévision des indices de réflexion des torpilles. En outre, l'entrepreneur a ajouté une amélioration comportant un modèle d'hélice nominale dans la prévision de l'indice de réflexion dans la plage des fréquences moyennes à élevées des sous marins ou des torpilles.

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Executive summary

Introduction

Advanced computational methods for the prediction of sound radiation and scattering from floating or submerged elastic bodies are being developed under collaborative research efforts between DRDC Atlantic and Martec. The development of these computational methods will serve as the basis for the expertise and tools necessary to solve current structures-related noise problems on CF vessels and to achieve further reductions in underwater acoustic signatures. These computational tools include AVAST which permits the numerical prediction of acoustic radiation and scattering from elastic structures in contact with infinite, half-space or finite depth fluid domains. AVAST combines both the finite element method for the structure and the boundary integral equation method for the fluid. The finite element method is used to predict the natural frequencies and related mode shapes of the structure in-vacuo. The boundary integral equation method is used to generate a system of equations relating structural displacements to fluid acoustic pressures.

Results

This contract addressed the need to extend the current capabilities of the AVAST software in order to provide a modeling tool suitable for predicting radiated noise and target strength of realistic ship structures. The contractor produced high fidelity underwater hull models of both the Canadian Patrol Frigate and CFAV Quest. For the purpose of acoustic target strength prediction, these models will include sufficient detail to allow for predictions at 50 kHz. In terms of radiated noise, the contractor developed a methodology for predicting hull surface accelerations, internal structural vibrations, and internal compartment radiated noise (up to approximately 50 Hz) due to an idealized acoustic source simulating propeller cavitation. The contractor investigated and found solutions for discrepancies between the Kirchhoff and conventional BIEM formulations when used for predicting torpedo target strength. In addition, the contractor provided a capability for including a nominal propeller model when predicting the medium-to-high-frequency target strength of a submarine or torpedo.

Significance

The upgraded AVAST code is now capable of predicting the underwater target strength at high frequencies for a two ship types and may now examine the effect on target strength of including a generic propeller in the model. The software may also be used to predict low frequency compartment noise and structural vibrations due to outboard acoustic sources, such as propeller cavitation.

Brennan, D.P., Wallace, J.C. 2007. High Frequency Target Strength Predictions. DRDC Atlantic CR 2007-043. Defence R&D Canada - Atlantic.

Sommaire

Introduction

Des méthodes de calcul perfectionnées permettant de prévoir le rayonnement acoustique et la diffusion du rayonnement par des structures élastiques flottantes ou immergées ont été mises au point dans le cadre d'une collaboration RDDC et Martec. L'élaboration de ces méthodes de calcul servira de fondement à l'expertise et fournira les outils nécessaires pour résoudre les problèmes actuels de bruit liés aux structures sur des navires des FC et pour mieux capter les signatures acoustiques sous marines. Les outils de calcul comprennent notamment le logiciel AVAST, permettant de calculer le rayonnement acoustique et la diffusion du rayonnement par des structures élastiques flottantes ou immergées dans un fluide infini, ou fini, occupant un demi-espace ou un volume défini. Le logiciel AVAST conjugue la méthode des éléments finis (MEF), pour la structure, et la méthode des équations intégrales de frontière, pour le fluide. La méthode des éléments finis (MEF) sert à prévoir les fréquences naturelles et les formes connexes de la structure in vacuo. La méthode des équations intégrales de frontière sert à produire un système d'équations qui relie les déplacements structuraux aux pressions acoustiques du fluide.

Résultats

Le but des travaux du présent contrat était d'améliorer le logiciel AVAST de manière à ce qu'il puisse modéliser adéquatement le bruit rayonné et l'indice de réflexion des structures de navires de manière plus réaliste. L'entrepreneur a créé des modèles de coques de navires sous marins de grande qualité, soit un modèle de la Frégate canadienne de patrouille et un modèle du Navire auxiliaire des Forces canadiennes Quest. Aux fins de la prévision de l'indice de réflexion des cibles acoustiques, ces modèles comprendront suffisamment de détails pour permettre des prévisions à 50 kHz. En ce qui a trait au bruit rayonné, l'entrepreneur a mis au point une méthode visant à prévoir les accélérations en surface de la coque, les vibrations des structures internes et le bruit rayonné des compartiments internes (jusqu'à environ 50 Hz) dû à une source acoustique théorique simulant une fréquence induite par l'hélice en cavitation. L'entrepreneur a examiné les écarts entre la méthode de Kirchhoff et la méthode des équations intégrales de frontière classiques dans la prévision des indices de réflexion des torpilles. En outre, l'entrepreneur a ajouté une amélioration comportant un modèle d'hélice nominale dans la prévision de l'indice de réflexion dans la plage des fréquences moyennes à élevées des sous marins ou des torpilles

Portée

Le logiciel AVAST amélioré est maintenant en mesure de prévoir l'indice de réflexion des cibles sous marines à des fréquences élevées pour deux types de navires et peut maintenant examiner les effets de l'indice de réflexion en incluant une hélice générique dans le modèle. Le logiciel peut également être utilisé pour prévoir le bruit des compartiments générant des basses fréquences et les vibrations de la structure dues à des sources acoustiques extérieures, comme une hélice en régime de cavitation.

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1. Introduction

Advanced computational methods for the prediction of sound radiation and scattering from floating or submerged elastic bodies are being developed under collaborative research efforts between DRDC Atlantic and Martec. The development of these computational methods will serve as the basis for the expertise and tools necessary to solve current structures-related noise problems on CF vessels and to achieve further reductions in underwater acoustic signatures. The computational tools under development include AVAST which permits the numerical prediction of acoustic radiation and scattering from elastic structures in contact with infinite, half-space or finite depth fluid domains. AVAST combines both the finite element method (FEM) for the structure and the boundary integral equation method (BIEM) for the fluid. The finite element method is used to predict the natural frequencies and related mode shapes of the structure in-vacuo. The boundary integral equation method is used to generate a system of equations relating structural displacements to fluid acoustic pressures. Through the proposed work, the current high frequency modelling capabilities of AVAST will be enhanced.

This contract addresses the need to extend the current capabilities of the AVAST software in order to provide a modeling tool suitable for predicting radiated noise and target strength of realistic ship structures. The contractor will use, as input, high fidelity models of both the Canadian Patrol Frigate and CFAV Quest. For the purpose of acoustic target strength prediction, these models will include sufficient detail to allow for predictions at 50 kHz. In terms of radiated noise, the contractor must develop a methodology for predicting hull surface accelerations, internal structural vibrations, and internal compartment radiated noise (up to approximately 50 Hz) due to an idealized acoustic source simulating propeller cavitation. The contractor will also investigate discrepancies between the Kirchhoff and conventional BIEM formulations when used for predicting torpedo target strength. In addition, the contractor will provide a capability for including a nominal propeller model when predicting the medium-to-high-frequency target strength of a submarine.

This work extends the existing capabilities of the existing AVAST computer code to examine a variety of issues related to the prediction of underwater target strength for complex structures. The AVAST code was developed under previous contracts including “Further Enhancements to the High Frequency Target Strength Prediction Capabilities of AVAST”, “Improving the High Frequency Performance of AVAST”, “Target Strength Prediction of Non-Rigid Structures Using AVAST”, “Target Strength Prediction Using AVAST”, and “Monostatic Target Strength Prediction Using AVAST”.

2. Submarine Target Strength

AVAST was enhanced with the capability to add a generic 7-bladed propeller (whose main diameter could be scaled) to an existing submarine model to allow for the more accurate prediction of medium-to-high-frequency acoustic target strength (using the Kirchhoff approximation) from the stern aspect of a submarine. The contractor will also demonstrate this capability by performing such an analysis with and without the propeller model present.

To deal with the propeller, as well interior compartment noise, two new types of boundary condition groups (“Exterior Panels” and “Interior Panels”) were created. These new groups did not require any special properties, as their sole purpose was to identify surface panels that are part of the propeller and the interior compartment. These groups were added to the list of boundary condition groups provided in the acoustic boundary condition dialog, as shown in the following figure.

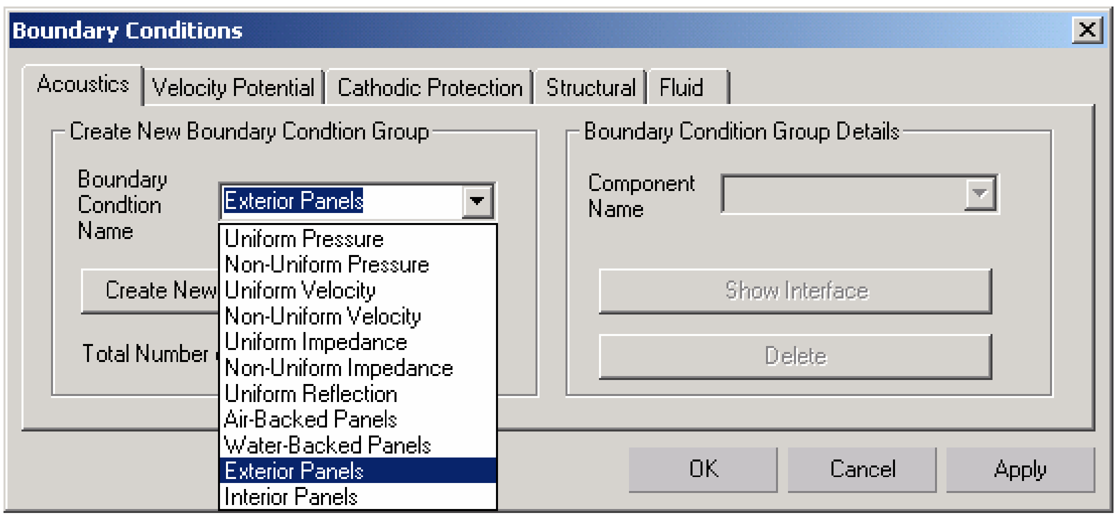

Figure 2.1: Boundary Condition dialog showing new groups

AVAST was modified to incorporate a propeller and interior compartment definition through the importation of two separate groups of panels, as stored in BEM files. This was accomplished by enhancing the existing structure importation feature with an ability to assign imported panels to a boundary condition group. The following figure shows the modified importation dialog. The new “Group” list displays all existing boundary condition groups. When the contents of a BEM file are to be appended to an existing surface, the newly imported panels will be assigned the specified group.

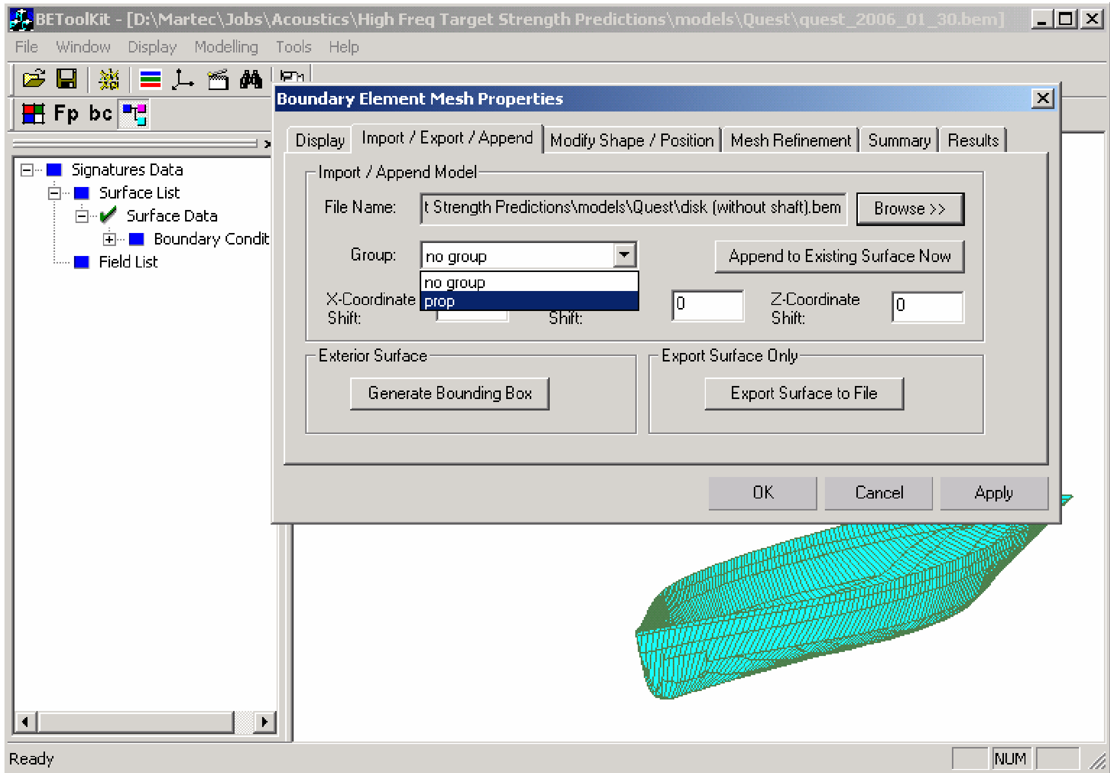

Figure 2.2: Modified model importation dialog

It was expected that a propeller, as described in a BEM file, might not be oriented so as to be properly aligned with the AVAST ship surface description. It is possible that when a propeller description is appended to an existing AVAST ship surface model it might need to be moved into the proper position. In order for a user to be able to accomplish this task, a new transformation feature was added to the boundary condition group dialog, as shown below.

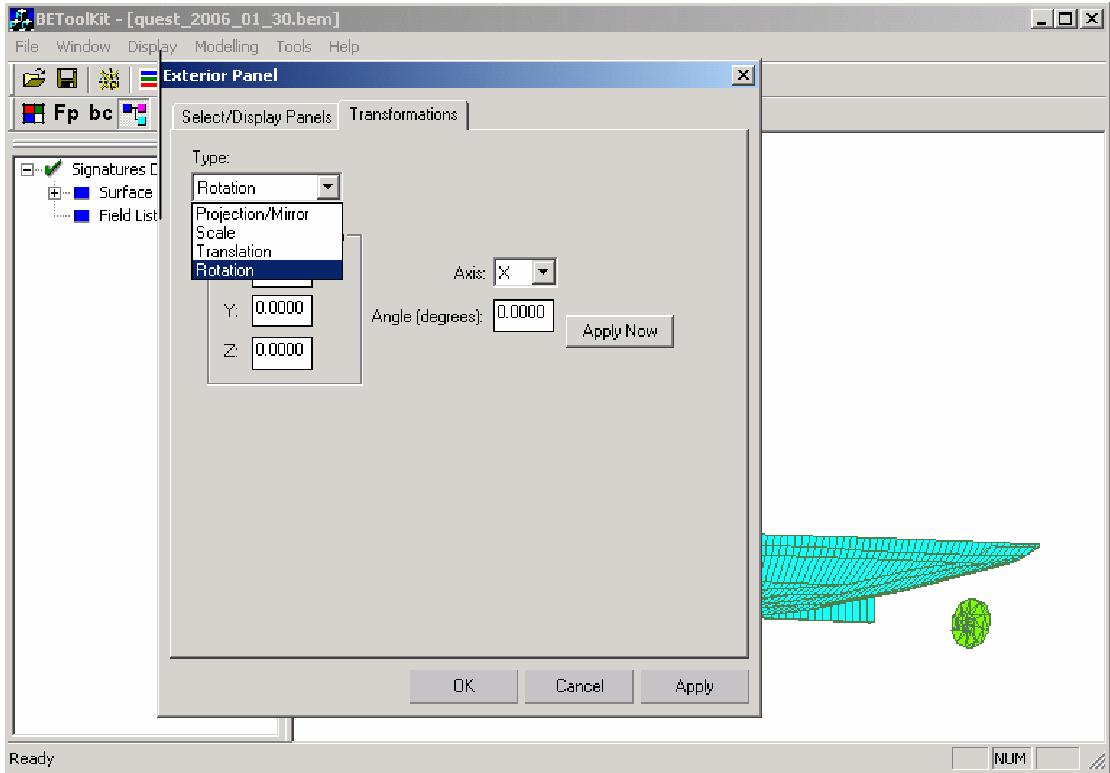

Figure 2.3: Boundary condition group transformation dialog

All required transformations, including projection/mirror, scale, translation and rotation, are linear 3D transforms, sometimes referred to as 3D affine transformations. A new class was created to handle all 3D affine transformations. This class was then used to manipulate all nodes in the specified boundary group.

Affine transformations have the following properties:

- preservation of lines and planes,
- parallel lines remain parallel,
- the first three columns contain the transformed coordinate frame,
- volumes are multiplied by the determinant of the inner 3x3 transformation matrix

In general a 3D affine transformation matrix is as follows:

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} x \\ y \\ z \\ 1 \end{Bmatrix}$$

where the sub-matrix contained in the first three row and columns describes the transformation of the coordinate frame (i.e. a projection, scale, shear or rotation) about the

coordinate frame origin. The vector represented by the fourth column is a simple translation vector.
There are five types of affine transforms. These include:

- projection/mirror
- scale
- rotation
- shear
- translation

A projection, or mirror, transformation matrix produces a mirror image of the transformed object about some plane. For simple projections in which the mirror plane passes through the origin and is aligned with the global axes the transformation matrix is as follows:

$$\begin{bmatrix} sx & 0 & 0 & 0 \\ 0 & sy & 0 & 0 \\ 0 & 0 & sz & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where one of s_x, s_y, s_z is equal to “–1” and the other two are equal to “1”.

A scale transformation expands coordinates along one, two or three orthogonal axes. The scaling factors along the three axes can be different from one another. When the scaling is along the global axes and the scaling origin coincides with the global origin, the transformation matrix would be as follows:

$$\begin{bmatrix} sx & 0 & 0 & 0 \\ 0 & sy & 0 & 0 \\ 0 & 0 & sz & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where s_x, s_y, s_z = scaling factors along the x, y, and z directions respectively

Rotation transformations represent a rigid-body rotation about some axis of rotation. There is no distortion of the transformed body. As an example, to rotate about the “X” axis the following transformation matrix would be employed:

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c & -s & 0 \\ 0 & s & c & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where $c = \cos(\theta)$
$s = \sin(\theta)$

For the most general (compound) rotation transformation the three columns in the upper left 3x3 matrix would contain the rotated X, Y and Z axes (i.e. direction cosines for the local X, Y and Z axes of the transformed space).

In all of the preceding transformations orthogonality is maintained. A shear transformation shears planar images in either one or two in-plane directions. For shears in the XY plane the transformation matrix would be:

$$\begin{bmatrix} 1 & f_{xy} & 0 & 0 \\ f_{yx} & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where f_{xy}, = shear factor in x direction
f_{yx}, = shear factor in y direction

A translation transformation simply shifts all points by a translation vector. The translation matrix is as follows:

$$\begin{bmatrix} 1 & 0 & 0 & x_0 \\ 0 & 1 & 0 & y_0 \\ 0 & 0 & 1 & z_0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where $\{x_0, y_0, z_0\}$ = translation vector

A transformation for which the transformation centre does not coincide with the global origin can be represented by a translation followed by a projection, scale, rotation or shear and then followed by another translation. The combined transformation matrix would be:

$$\begin{bmatrix} m_{11} & m_{12} & m_{13} & (x_0 - m_{11} \cdot x_0 - m_{12} \cdot y_0 - m_{13} \cdot z_0) \\ m_{21} & m_{22} & m_{23} & (y_0 - m_{21} \cdot x_0 - m_{22} \cdot y_0 - m_{23} \cdot z_0) \\ m_{31} & m_{32} & m_{33} & (z_0 - m_{31} \cdot x_0 - m_{32} \cdot y_0 - m_{33} \cdot z_0) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where $\{x_0, y_0, z_0\}$ = translation origin

Group transformations are performed on all nodes that are associated with the group panels. Assembling this list of nodes required identifying all nodes on all panels in the group. Repeated nodes had to be eliminated from the list so as to avoid applying the transformation more than once to any one node.

One final enhancement involved panel normals. It was necessary to be able reverse the normals of all panels in a propeller group or an interior compartment group. While it is possible that a user could be required to ensure that normals were pointed in the correct direction when creating the BEM file, subsequent user-mirror transformations to panels in a group would change panel normals.

Consequently, the functionality to manipulate normals for all panels in a surface was added to the boundary condition group dialog. The following figure shows the new normal controls.

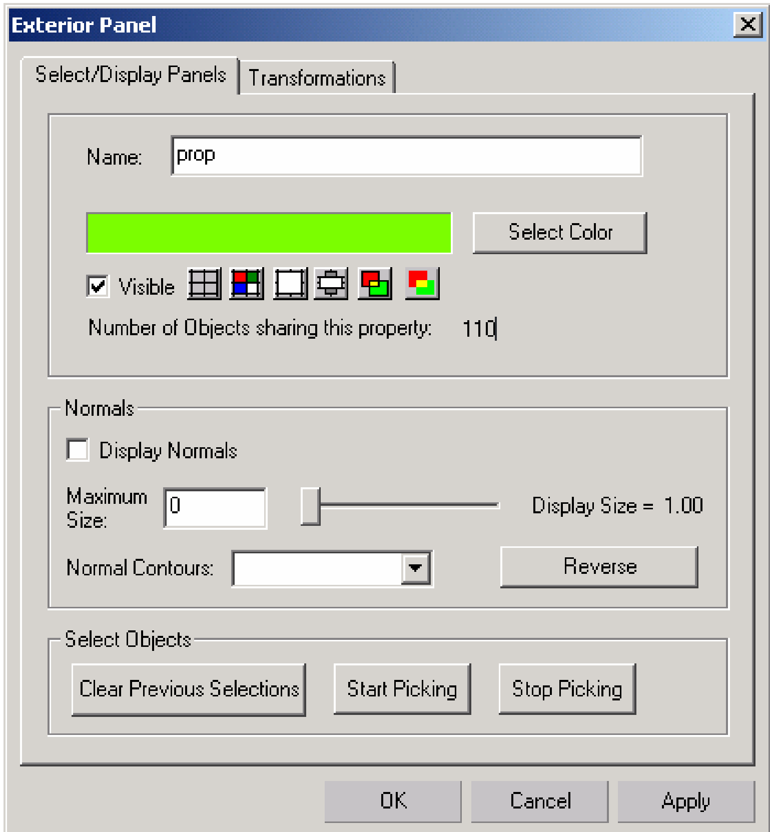

Figure 2.4: Panel normal controls for boundary condition group

3. Predicting Compartment Vibrations from Propeller Cavitation

The contractor will examine the prediction of shipboard compartment vibrations from propeller cavitation. With an assumed point source of cavitation, the contractor will establish and demonstrate a methodology to predict hull surface accelerations, internal structural vibrations, and internal compartment radiated noise. The frequency range of interest should be that available with a finite element model (e.g., approximately 50 Hz for a model of CFAV Quest). The contractor will demonstrate the capability using CFAV Quest and data provided by the scientific authority.

3.1 Implementation

In simple terms, this involved performing a coupled bistatic target strength analysis, in which the elastic response of a structure to a remote acoustic source is computed, is followed by a simple radiation (added mass) analysis, in which the noise levels inside a closed domain are computed. While both types of analyses already existed in AVAST, changes were necessary in order to use these for compartment noise analyses.

The coupled bistatic target strength analysis required definition of the exterior (wetted) surface and the interior (compartment) surface. Hence, a compartment noise analysis model must include the wetted hull surface plus the interior compartment. Identification of wetted hull surface and the interior compartment involved using the boundary condition groups developed as part of item 1. The wetted hull surface panels must be placed in an “exterior” group while the interior compartment panels must be placed in an “interior” group.

The interior compartment mesh, the wetted hull mesh and the structural mesh (from which the dry natural frequencies are computed) must use the same list of nodes in order for the structural responses to be properly applied to the compartment panels. This required the addition of a new control that controls the merging of nodes when a mesh is to be appended to an existing mesh. When the second mesh is to be imported the “Merge Nodes” checkbox, as shown in the following figure, must be checked in order to ensure that the nodes in the second mesh are not added to the previously defined list of nodes.

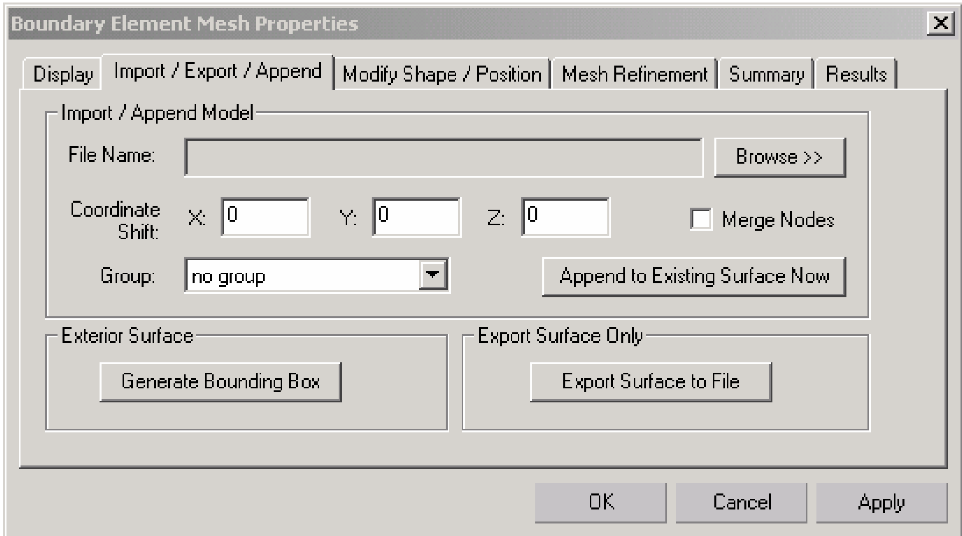

Figure 3.1: Model append dialog

The bistatic target strength analysis uses an external acoustic source and the elastic structural response to compute normal velocities on interior panels. This analysis must ensure that only exterior group panels are recognized as wetted panels and that normal velocities are computed for only the interior panels. This meant that AVAST had to be modified so that only the subset of panels identified by the exterior group would make up the wetted surface and only the subset of panels identified by the interior group would used when computing the normal velocities. Computation of normal velocities on the interior panels required that nodal displacements be converted to normal panel velocities for all panels in the interior group.

Nodal displacements are computed by multiplying the matrix of mode shapes (eigenvectors) by the modal displacements. Since displacements are in the frequency domain, nodal velocities are computed by multiplying displacements by “iω”.

$$\{\upsilon\} = i\omega[\phi]\{\xi\}$$

Normal panel velocities are then computed by taking the average of the normal component of the nodal velocities at the panel vertices.

In the second part of a compartment vibration analysis in AVAST (a radiation analysis) it was necessary to isolate the interior group and analyze the mesh using the normal velocities computed in the previous part (the bistatic target strength analysis). Field points in the interior compartment are needed so that pressures in the interior of the compartment can be calculated. This required use of different fluid properties (i.e. properties for air, not seawater).

3.2 Model generation

The steps required for a complete analysis are as follows:

1) **Structural analysis**
    a. Generate a Trident FEA finite element model of the ship including the wetted hull surface, the interior compartment and all other structural components. There should be no boundary conditions applied to the model.
    b. Using VAST compute the "dry" natural frequencies.
    c. Extract two sub-models, one containing only the wetted surface and the second containing only the interior compartment. If some elements are common to both sub-models then those common elements should be included in both sub-models, even though this will cause the generation of coincident panels in AVAST. Both models should include the entire list of nodes used in the natural frequency analysis.
    d. Convert sub-models to AVAST (BEM) files. These BEM files should include only node and panel definitions, and no surfaces or other AVAST objects. Ensure that panel normals are defined in a consistent way. That is, all normals in the wetted surface model should point either away from the surrounding fluid or into the fluid. Similarly, normals for all panels in the compartment model should point away from the compartment interior or into the interior.
2) **AVAST model generation**
    a. Define one exterior panel group and one interior panel group.
    b. Using the "surface mesh" modeling option import the wetted surface mesh and assign it to the exterior group.
    c. Using the "surface mesh" modeling option import the interior compartment mesh and assign it to the interior group.
    d. Ensure that panel normals are pointed in the proper direction. For panels on the wetted surface normals should point away from the surrounding fluid domain. For panels in the interior compartment group normals should point away from the compartment interior.
    e. Import natural frequencies and mode shapes. Go to the Boundary Conditions dialog and select the "structural" tab. From there, the VAST file containing the frequencies and mode shapes can be selected.
    f. Specify properties for the surrounding fluid domain. Under "Boundary Conditions" select the "fluid" tab. Properties include the speed of sound and fluid density as well as the free surface elevation and the orientation of the free surface.
    g. Create field points. These are the locations of points inside the compartment interior where noise levels are to be computed. There are several methods for creating field points. Select the Arc method. Input parameters include the centre of the arc, axis of rotation, starting point for the arc, number of field points to be generated and the total angle subtended by the arc. The results series of field points should be inside the compartment.

3) **AVAST Solver** (from the “Tools” menu item select the “analysis solver” wizard)
   a. The first solver input page contains a prompt for a file path. The specified directory will be used for subsequent file I/O.
   b. This is following by a second page on which the analysis type is specified. Select “Compartment Noise”. In addition specify the source frequency. Specify a single frequency. If more than one source frequency is to be used, then a separate analysis will be required for each frequency. This page also contains controls for interior fluid properties (speed of sound and density). These are the properties for the fluid inside the compartment interior.
   c. On the third page are controls for specification of the source location.
   d. The final solver page contains controls for various solver options. The only active option is to specify “LU decomposition”. This option should be selected.
   e. Press the “Run Solver” button to begin the analysis.
4) **AVAST Analysis Results**
   a. Field point results can be accessed via the scenegraph under the Field point item. This provides a polar plot of field point pressures.
   b. Alternately, the field point pressure values are stored in an ASCII file named “AVAST.OUT”.

3.3 Tests

Two models were used to test the process of creating and analyzing compartment noise models. The first model is a simple cylinder with one interior deck that connects the cylinder walls to a single interior compartment. The second model is the DRDC Atlantic research vessel Quest. Noise levels in the combined elect/engrs store and general store resulting from simulated propeller noise were computed.

3.3.1 Simple cylinder with interior compartment

The complete analysis package was first tested with a model of a fully submerged cylinder with an interior deck and compartment that sits on the deck. The following figure shows a cut-away view of the structural model.

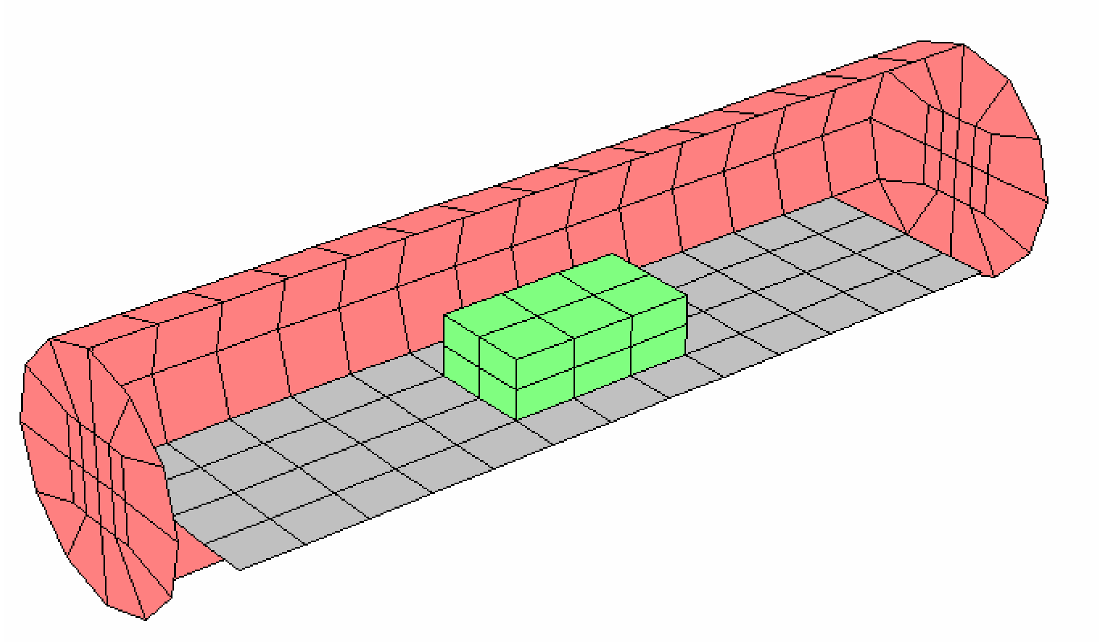

Figure 3.2: Sample cylinder model used for compartment noise analysis

The cylinder has a radius of 0.75 m and a length of 3 m. The interior compartment is attached to the sides of the cylinder. All structural components were assigned steel material properties and were given a thickness of 2 mm. The first 26 natural frequencies (including six rigid body motions) were computed using Trident FEA.

A single acoustic source was placed 3.5 m from one end of the cylinder and 1 m off the centreline. A circular arrangement of field points was placed inside the compartment, as shown below.

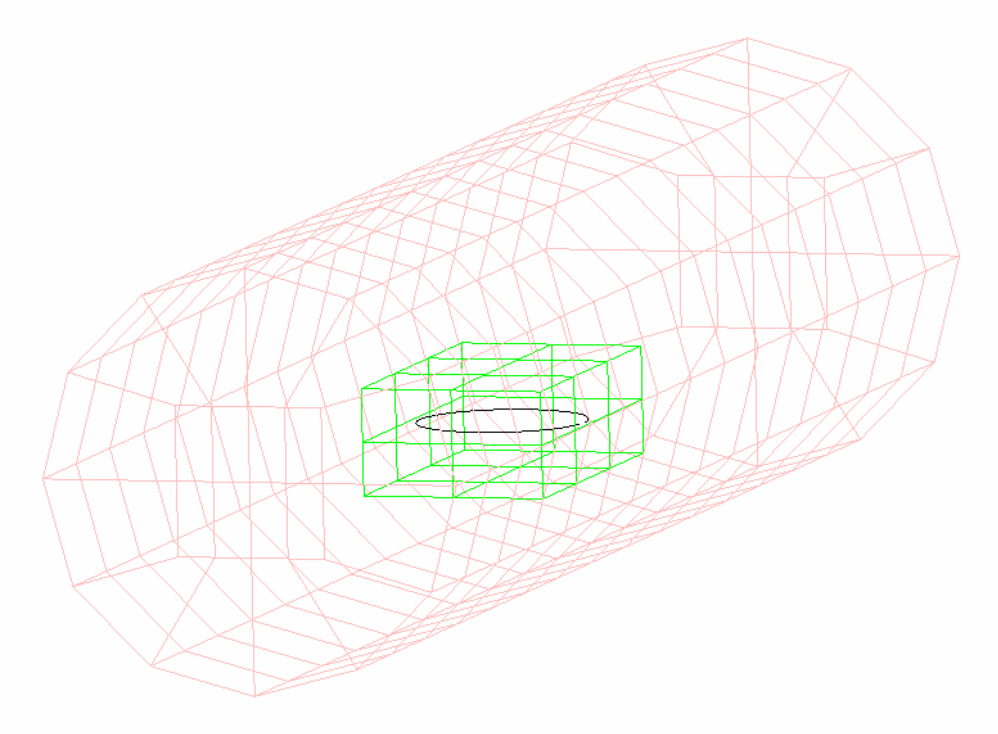

Figure 3.3: Field point locations for cylindrical compartment noise model

The 20 significant natural frequency (non-rigid body frequencies) ranged from 28.68 to 99.46 cycles/sec.

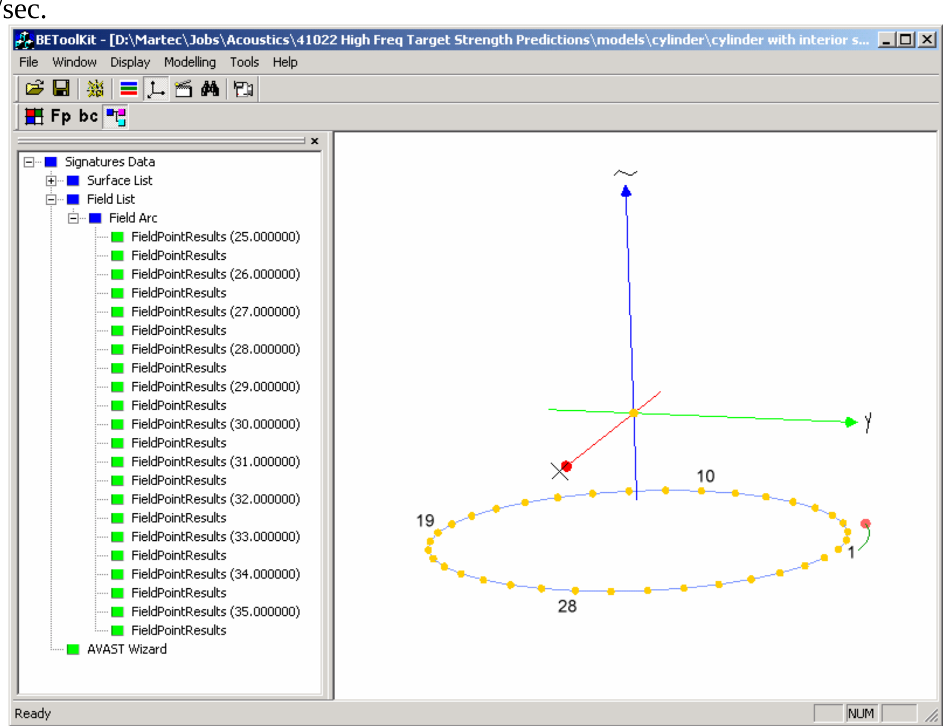

Figure 3.4: Screen capture of compartment noise analysis results

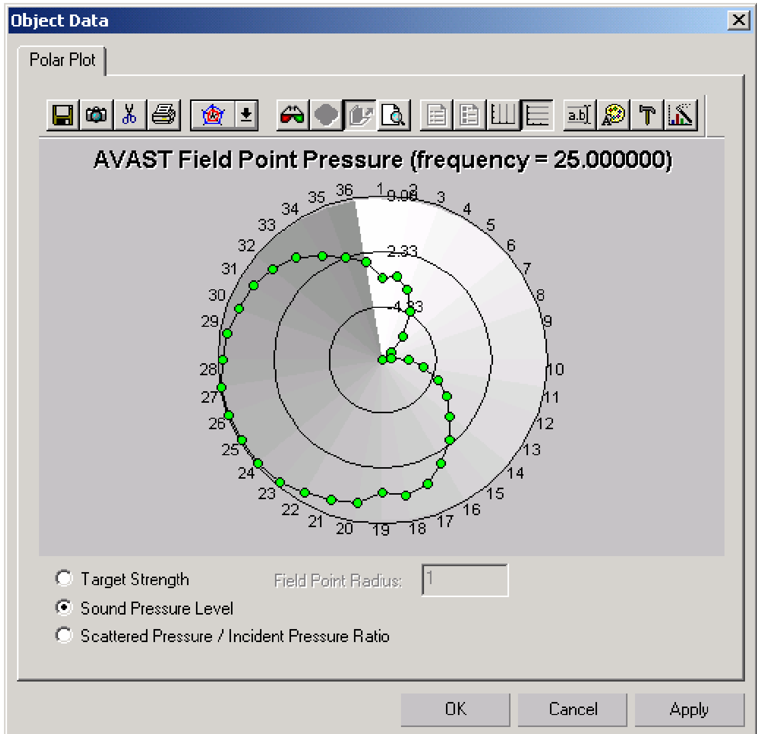

Figure 3.5: Plot of compartment noise results for cylindrical model

It should be noted that all results are based on a source of unit strength.

A brief study of the effect of acoustic source location was performed. Initially, the source was placed 0.1 meters (equal to ½ size of one panel) away from the side of the cylinder. This distance was increased to 0.2m (1 panel), 0.4m (2 panels)), 0.6m (3 panels) and 1.0m (5 panels). A source frequency of 32 Hz was used. Results are shown below. Noise levels were calculated by scaling the computed pressures. The final two figures show how the pressure at the first compartment panel varies with distance from the acoustic source to the cylinder.

Table 3.1 Cylinder model compartment panel pressures (Pa)

	distance from source to cylinder				
Panel #	0.1	0.2	0.4	0.6	1.0
1	7.45E-04	2.06E-04	1.42E-04	1.40E-04	8.37E-05
2	7.64E-04	2.23E-04	1.41E-04	1.37E-04	8.20E-05
3	7.89E-04	2.38E-04	1.35E-04	1.31E-04	7.85E-05
4	9.69E-04	2.95E-04	1.45E-04	1.61E-04	1.09E-04
5	9.91E-04	3.08E-04	1.43E-04	1.59E-04	1.09E-04
6	1.03E-03	3.29E-04	1.37E-04	1.56E-04	1.08E-04
7	1.90E-03	3.46E-04	7.11E-04	6.48E-04	3.81E-04
8	1.96E-03	3.49E-04	7.31E-04	6.66E-04	3.92E-04
9	1.89E-03	3.48E-04	7.12E-04	6.47E-04	3.80E-04
10	2.05E-03	2.99E-04	5.57E-04	5.35E-04	3.10E-04
11	2.12E-03	3.09E-04	5.72E-04	5.50E-04	3.18E-04
12	2.05E-03	2.98E-04	5.58E-04	5.34E-04	3.09E-04

	distance from source to cylinder				
Panel #	0.1	0.2	0.4	0.6	1.0
13	1.49E-03	3.11E-04	5.88E-04	5.37E-04	3.23E-04
14	1.54E-03	3.14E-04	6.06E-04	5.54E-04	3.33E-04
15	1.51E-03	3.08E-04	5.89E-04	5.39E-04	3.24E-04
16	8.56E-04	3.15E-04	3.01E-04	2.63E-04	1.60E-04
17	8.66E-04	3.09E-04	3.11E-04	2.74E-04	1.67E-04
18	8.61E-04	2.93E-04	3.04E-04	2.70E-04	1.65E-04
19	1.48E-03	2.99E-04	5.47E-04	4.98E-04	2.94E-04
20	8.44E-04	2.39E-04	2.54E-04	2.32E-04	1.38E-04
21	1.54E-03	2.38E-04	4.36E-04	4.11E-04	2.36E-04
22	8.91E-04	2.33E-04	2.13E-04	2.03E-04	1.22E-04
23	1.50E-03	2.37E-04	4.33E-04	4.06E-04	2.33E-04
24	8.93E-04	2.56E-04	2.06E-04	1.95E-04	1.17E-04
25	1.45E-03	3.06E-04	5.45E-04	4.94E-04	2.91E-04
26	8.36E-04	2.63E-04	2.48E-04	2.23E-04	1.32E-04
27	1.53E-03	2.39E-04	4.14E-04	3.91E-04	2.22E-04
28	1.59E-03	2.44E-04	4.23E-04	4.01E-04	2.27E-04
29	1.55E-03	2.41E-04	4.16E-04	3.93E-04	2.23E-04
30	8.84E-04	2.02E-04	1.99E-04	2.02E-04	1.29E-04
31	8.88E-04	1.89E-04	2.04E-04	2.07E-04	1.32E-04
32	8.88E-04	1.87E-04	2.05E-04	2.07E-04	1.32E-04

Table 3.2 Cylinder model compartment panel noise levels (dB)

	distance from source to cylinder				
Panel #	0.1	0.2	0.4	0.6	1.0
1	31.42	20.24	17.05	16.88	12.43
2	31.64	20.94	16.96	16.72	12.26
3	31.92	21.51	16.56	16.35	11.88
4	33.70	23.37	17.20	18.09	14.74
5	33.90	23.75	17.06	18.02	14.74
6	34.24	24.33	16.71	17.83	14.65
7	39.53	24.76	31.02	30.20	25.59
8	39.81	24.83	31.26	30.45	25.85
9	39.51	24.82	31.03	30.20	25.57
10	40.22	23.49	28.90	28.54	23.79
11	40.52	23.78	29.13	28.79	24.04
12	40.20	23.45	28.91	28.54	23.77
13	37.45	23.83	29.37	28.58	24.17
14	37.72	23.92	29.63	28.85	24.44
15	37.55	23.76	29.39	28.61	24.20
16	32.63	23.94	23.54	22.38	18.05
17	32.73	23.79	23.83	22.74	18.43
18	32.68	23.32	23.64	22.62	18.32
19	37.39	23.50	28.74	27.93	23.33
20	32.51	21.56	22.07	21.27	16.77
21	37.71	21.52	26.77	26.26	21.43
22	32.98	21.33	20.54	20.11	15.68
23	37.51	21.46	26.70	26.16	21.32
24	33.00	22.16	20.26	19.76	15.36
25	37.19	23.69	28.70	27.85	23.25
26	32.42	22.39	21.88	20.93	16.39
27	37.67	21.56	26.33	25.82	20.90
28	37.99	21.74	26.51	26.03	21.12
29	37.77	21.61	26.36	25.87	20.95
30	32.91	20.10	19.96	20.07	16.21
31	32.94	19.49	20.19	20.31	16.41
32	32.94	19.42	20.21	20.31	16.38

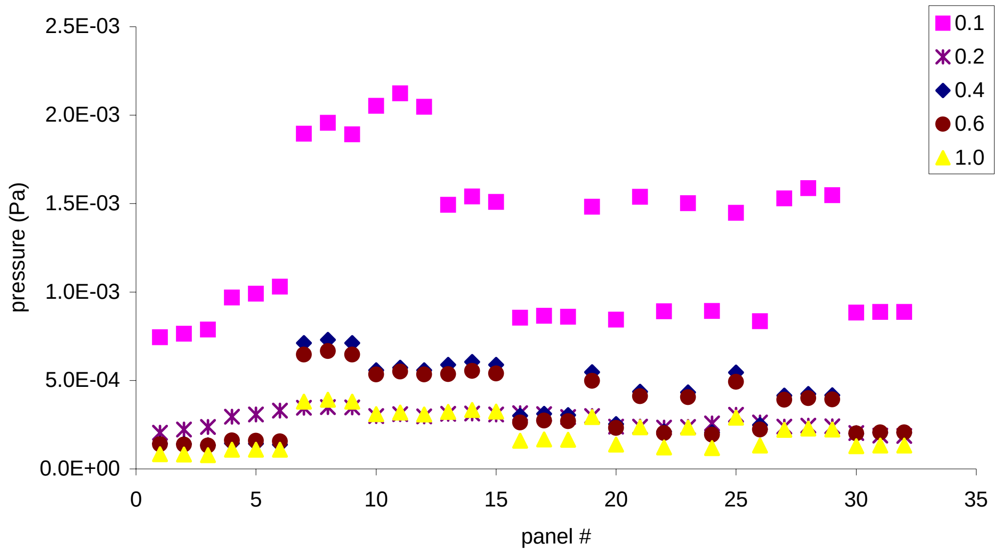

Figure 3.6 Cylinder model field point pressures (from source location study)

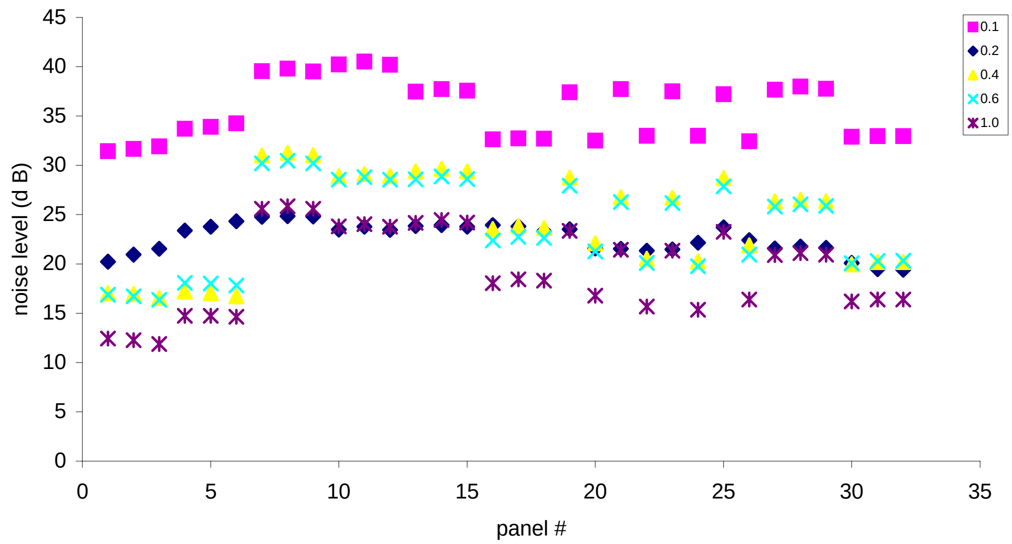

Figure 3.7 Cylinder model field point noise levels (from source location study)

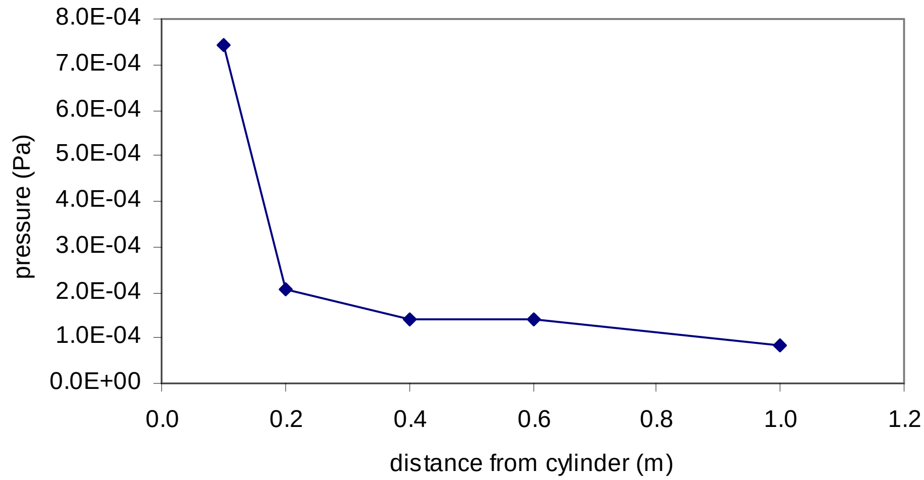

Figure 3.8 Cylinder model panel pressure as function of source distance

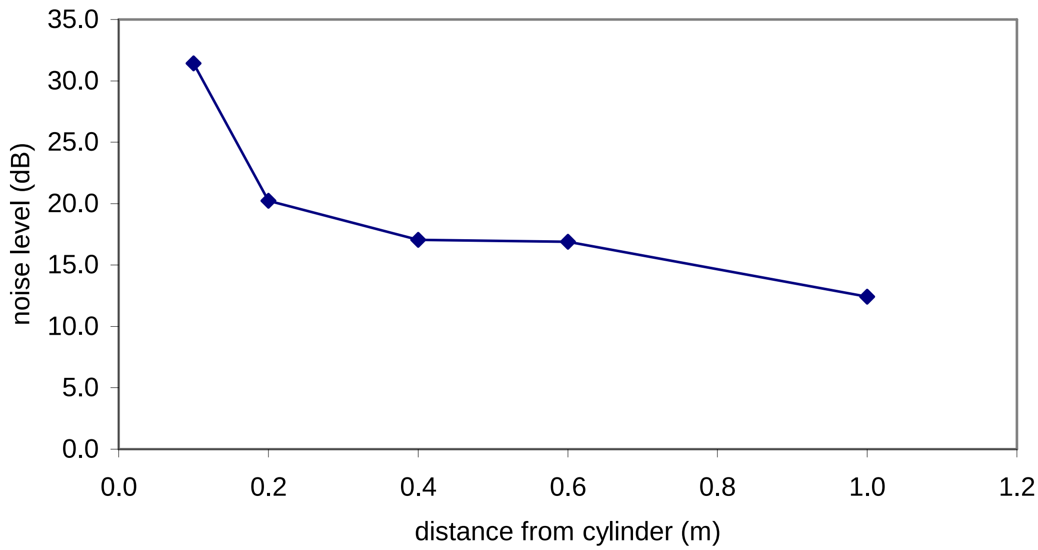

Figure 3.9 Cylinder model panel noise level as function of source distance

3.3.2 Quest

The scientific authority was interested in noise levels in the elec/engr store and general store resulting from propeller cavitation. The following two figures show the location of the stores.

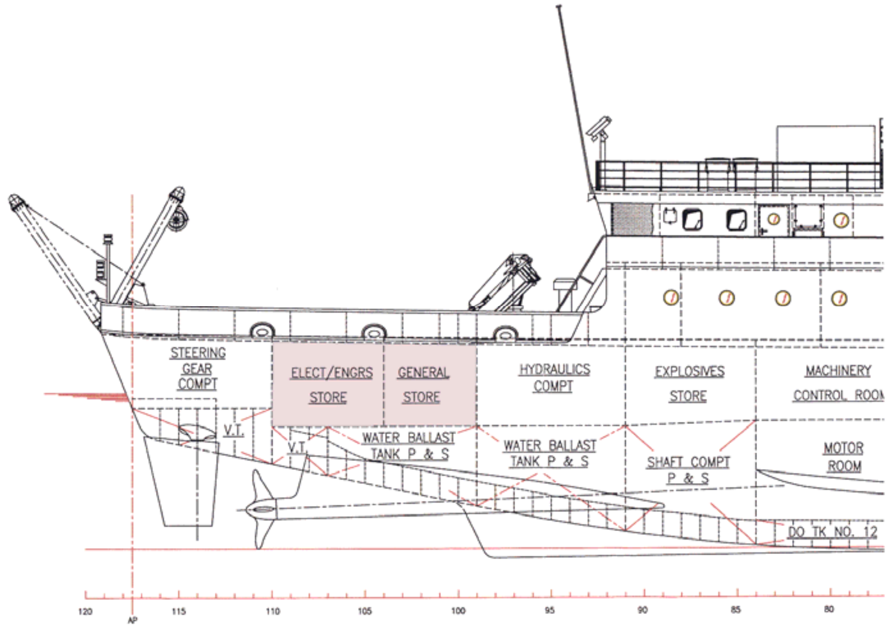

Figure 3.10 Elevation view of Quest showing stores

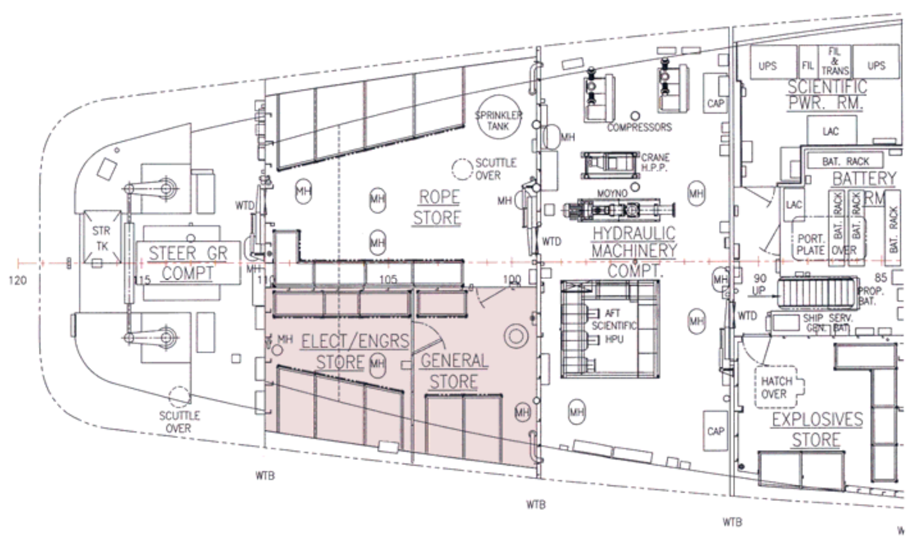

Figure 3.11 Plan view of Quest showing stores

The second figure shows what appears to be a non-structural partition between the two stores. For purposes of the compartment noise analysis this partition was ignored.

At the recommendation of the scientific authority the acoustic source was placed so to represent a starboard blade tip at top-dead-centre (TDC). It was estimated that this would place the source at coordinates of 67.666m aft of the forward perpendicular, 2.435m off the centerline and 2.866m up from the baseline. This corresponds to frame 111.

The original Quest structural model was supplied by DRDC Atlantic. In this model a longitudinal bulkhead separating the elec/engrs store and general store from adjacent rooms was not included. Hence this model was modified so as to include the longitudinal bulkhead. At the same time model units were converted from inches to meters so as to make model importation into AVAST more straightforward. It was noted that on the outer hull surface of the model there was a line of nodes at a vertical location of 5.4864m (216 inches or 18 feet) from baseline. For purposes of this analysis it was decided to use this line of nodes as the upper limit for the wetted surface model. The following two figures show the structural model, including the waterline and the internal compartment. In the second figure a portion of the deck has been removed to reveal the complete interior compartment.

The first 50 natural frequencies were computed using the Trident FEA “subspace iteration” option. Since no boundary conditions were imposed, the first six frequencies corresponded to the six rigid-body modes. By including a representation of the wetted surface, Trident FEA was able to compute “wet” modes as well as “dry” modes. The following table shows the natural frequencies calculated by Trident FEA. In addition the table also shows the (wet) frequencies calculated by AVAST.

Table 3.3 Quest Natural Frequencies

	VAST		AVAST		VAST		AVAST
	(in air)	(in water)			(in air)	(in water)	
1	0.00	0.00	0.0000	26	14.4	13.8	13.7817
2	0.00	0.00	0.0000	27	14.6	13.9	13.8996
3	0.00	0.00	0.0000	28	14.8	14.4	14.3787
4	0.00	0.00	0.0000	29	15.0	14.5	14.5360
5	0.00	0.00	0.0000	30	15.2	14.6	14.6226
6	0.00	0.00	0.0000	31	15.2	14.8	14.8326
7	4.20	3.52	3.5154	32	15.3	15.0	14.9962
8	5.44	4.66	4.6727	33	15.5	15.1	15.0652
9	6.49	5.45	5.4363	34	15.7	15.2	15.1747
10	8.75	7.96	7.9557	35	15.8	15.3	15.3280
11	9.68	8.15	8.1548	36	16.0	15.5	15.4687
12	10.3	9.28	9.2680	37	16.1	15.8	15.7854
13	10.5	10.2	10.2144	38	16.1	15.9	15.9300
14	11.7	10.6	10.6474	39	16.4	16.0	15.9647
15	12.2	11.2	11.2609	40	16.6	16.1	16.0700
16	12.5	12.0	12.0100	41	16.7	16.1	16.1346
17	12.5	12.2	12.2396	42	16.8	16.3	16.3191
18	12.6	12.3	12.3857	43	17.0	16.5	16.5307
19	13.0	12.5	12.4840	44	17.1	16.6	16.6278
20	13.1	12.5	12.5223	45	17.2	16.9	16.9085
21	13.4	12.5	12.5398	46	17.5	17.0	17.0268
22	13.6	12.8	12.8673	47	17.6	17.3	17.2583
23	13.8	13.1	13.0924	48	17.9	17.5	17.5099
24	13.9	13.3	13.2576	49	18.2	17.6	17.5805
25	14.2	13.7	13.6687	50	18.3	18.1	18.1365

Before the model could be imported into AVAST it was necessary to isolate the wetted surface and the interior compartment. It is important to note that the starboard limit of the compartment shares elements with the wetted surface. Hence these elements were common to both sub-models. Trident FEA modules were used to distinguish the different collection of elements (wetted surface elements, interior compartment elements and elements common to both). Care was taken to ensure that a complete list of structural nodes was saved in each exported sub-model and that the node numbering was preserved. This was important because the list of nodes imported into AVAST must correspond to the nodes identified in the natural frequency file.

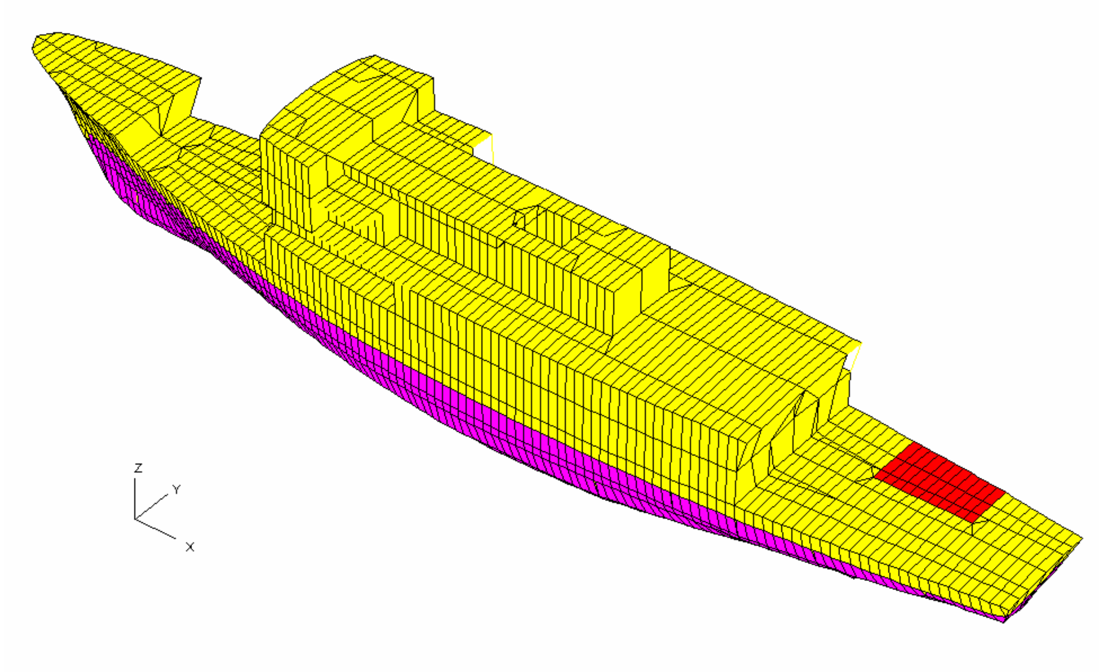

Figure 3.12 Quest structrual model

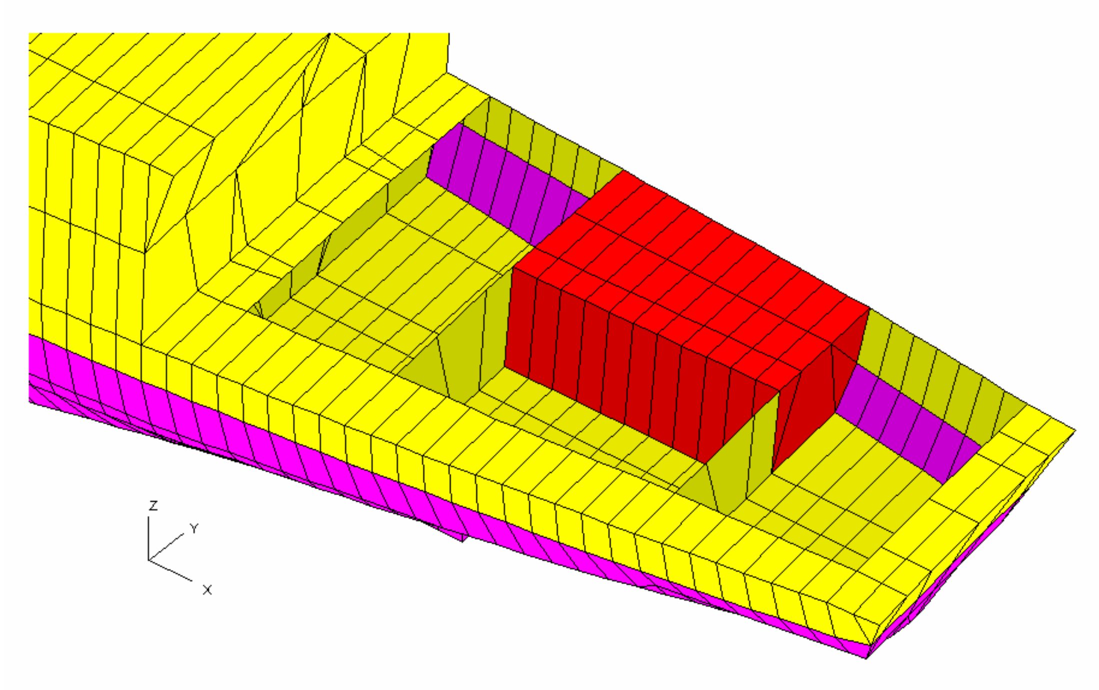

Figure 3.13 Quest structrual model (showing interior compartment)

Following calculation of natural frequencies and generation of BEM files for the wetted surface and interior compartment, the two sub-models were imported into AVAST. The following figure shows the AVAST model.

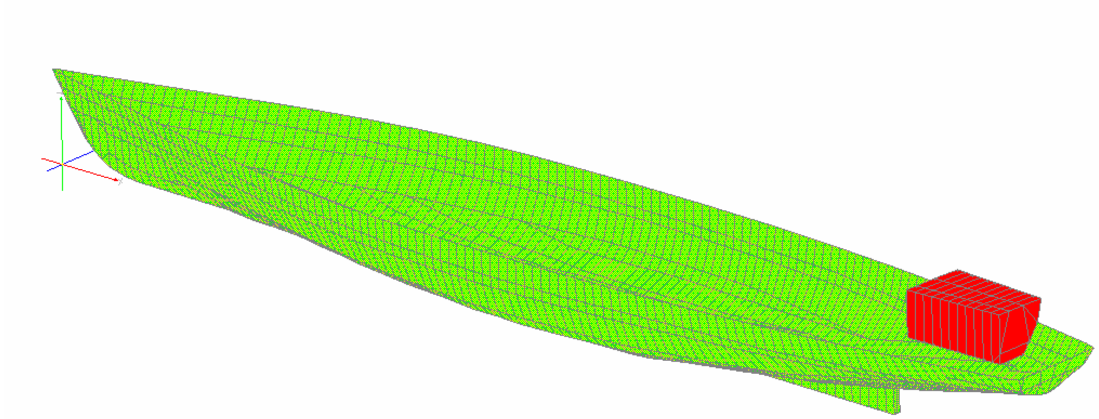

Figure 3.14 Quest AVAST model

In order to compare with sensor results, which were placed on decks and bulkheads pressures were recorded for specific panels, as shown below.

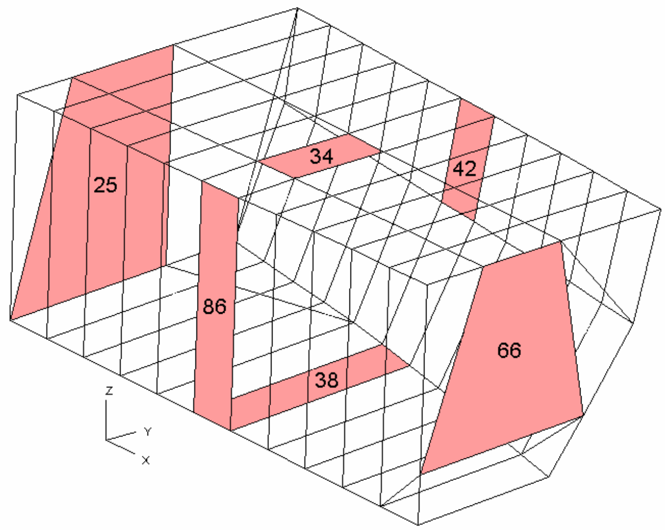

Figure 3.15 Quest compartment panels for computation of pressures

Panel pressures were computed for four different acoustic source frequencies: 4.2 Hz, 8.5 Hz, 12.8 Hz and 17.1 Hz. The 4.2 Hz and 12.8 Hz correspond with the first and 16th (non-rigid mode) natural frequencies. Field point pressures and sound levels are listed in the following table as well as the following figures.

Noise levels were calculated by scaling the computed pressures as follows:

$$NL = 20 \cdot \log_{10}\left(\frac{P}{2 \cdot 10^{-5}}\right)$$

where NL = noise level (dB)
P = pressure (Pa)

As was the case for the previous model, all results are based on an acoustic source of unit strength.

Table 3.4 Quest Panel Pressure Results

Panel #	freq = 4.2 Pressure (Pa)	freq = 4.2 Noise Level (dB)	freq = 8.5 Pressure (Pa)	freq = 8.5 Noise Level (dB)	freq = 12.8 Pressure (Pa)	freq = 12.8 Noise Level (dB)	freq = 17.1 Pressure (Pa)	freq = 17.1 Noise Level (dB)
25 (fore)	1.41E-05	-3.02	2.22E-06	-19.08	6.54E-06	-9.71	2.48E-05	1.87
34 (top)	1.70E-04	18.59	8.31E-05	12.37	5.88E-05	9.36	2.62E-04	22.35
38 (bottom)	1.76E-05	-1.12	8.87E-06	-7.06	4.90E-06	-12.22	2.05E-05	0.23
42 (outboard)	6.73E-06	-9.45	3.09E-05	3.79	9.70E-06	-6.29	3.08E-05	3.75
66 (stern)	3.26E-05	4.24	2.99E-05	3.49	1.76E-05	-1.10	4.99E-05	7.95
86 (inboard)	1.21E-05	-4.34	8.35E-06	-7.58	3.58E-06	-14.94	1.97E-05	-0.13

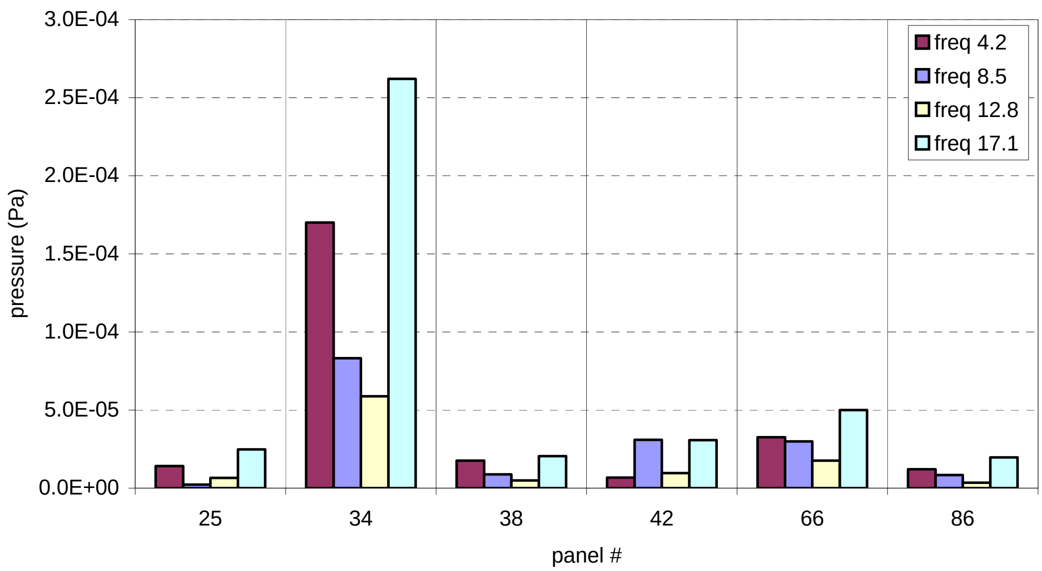

Figure 3.16 Quest model compartment panel pressures

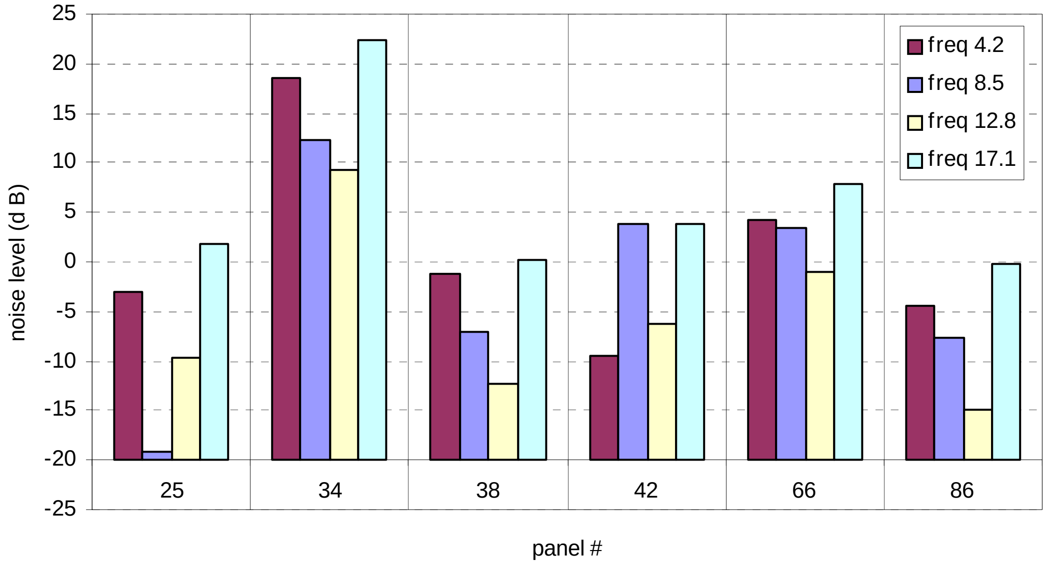

Figure 3.17 Quest model compartment panel noise levels

4. Evaluate AVAST Formulations for High Frequency Target Strength

In a recent series of high-frequency AVAST target strength studies, discrepancies between the Kirchhoff and BIEM formulations were discovered. These studies, which involved studying the monostatic target strength of torpedo and cylinder bodies, showed generally good agreement for angles corresponding to broadside and endcap angles. However, the results generated by the BIEM algorithm would often predict large end and broadside side lobes that could not be justified from the underlying physics.

In the report that follows, the results from a number of high-frequency monostatic target strength simulations, involving cylindrical and torpedo-like bodies, will be presented. In each case, numerical results have been generated using the conventional boundary element method, the Burton and Millar boundary element method, and the Kirchhoff approximation.

Model Results

For the purposes of this investigation high-frequency monostatic target strength predictions were generated for three bodies: a cylinder (see figures 1-6), the main body of a torpedo (see Figures 7-14), and a full torpedo, complete with a tail and fins (see Figures 15-20). All simulations were conducted at a frequency of 7.5 kHz. A review of the results clearly shows how the use of the Burton and Millar boundary element formulation provides far superior agreement to the high-frequency Kirchhoff than does the conventional boundary element formulation. As a result, it must be concluded that the cause of the earlier discrepancies found between the Kirchhoff and BIEM formulations were due to irregular frequency problems (the Burton and Millar formulation corrects automatically for irregular frequencies).

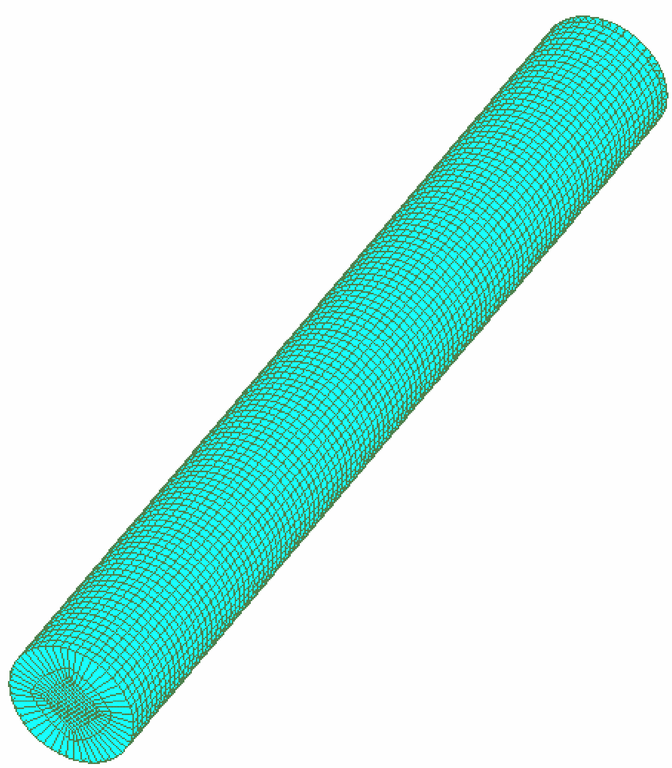

Figure 4.1: AVAST Cylinder Model

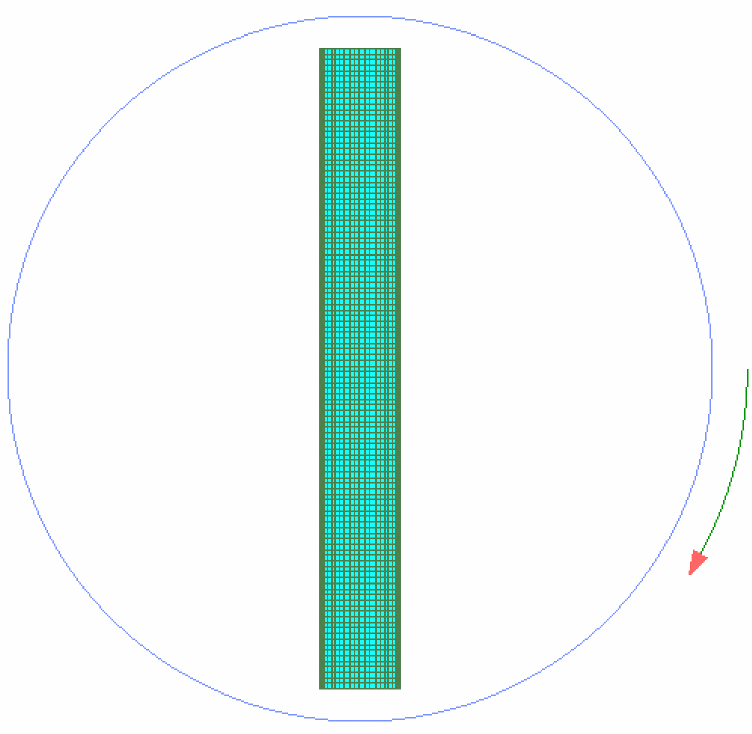

Figure 4.2: Orientation of Cylinder Field Points

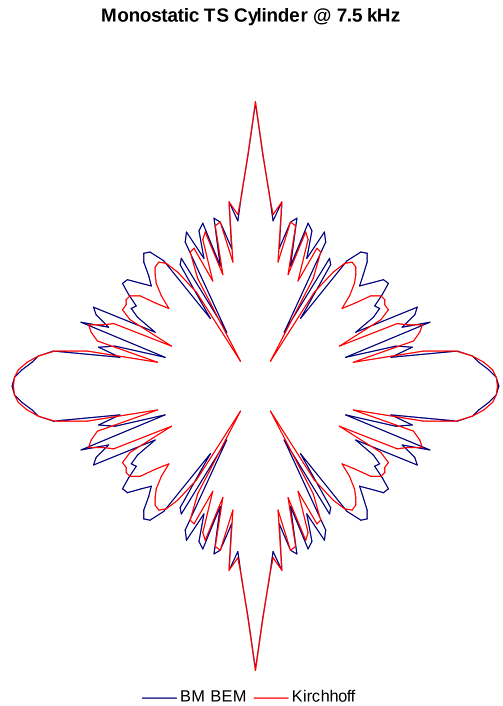

Figure 4.3 Monostatic TS of Cylinder at 7.5 kHz: Kirchhoff vs Burton-Millar BEM

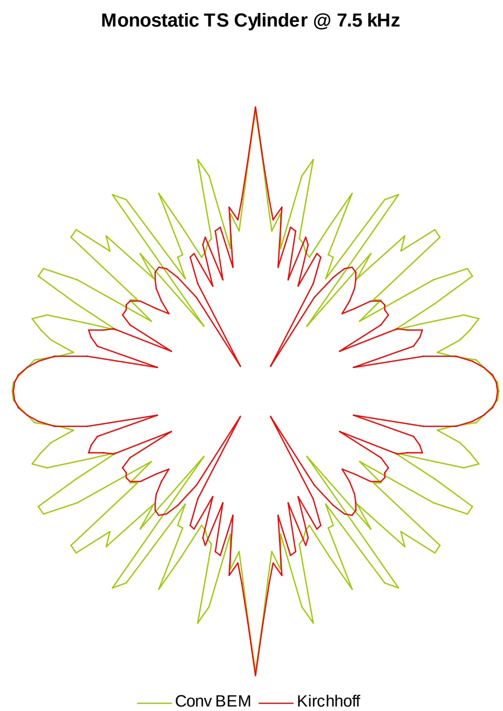

Figure 4.4: Monostatic TS of Cylinder at 7.5 kHz: Kirchhoff vs Conventional BEM

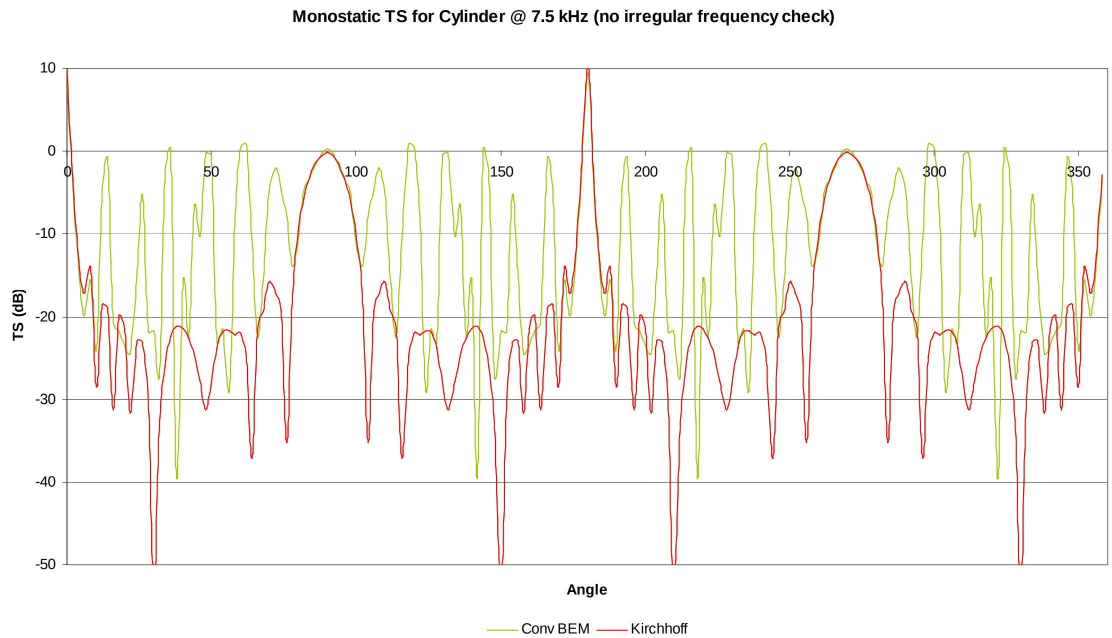

Figure 4.5: Monostatic TS of Cylinder at 7.5 kHz (Line Plot): Kirchhoff vs Conventional BEM

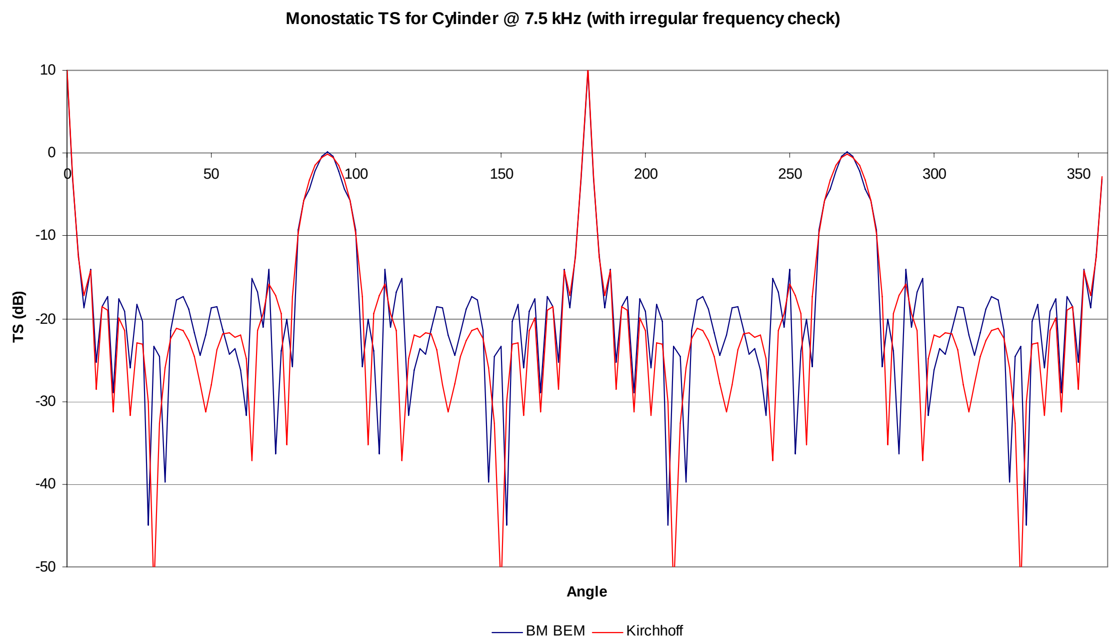

Figure 4.6 Monostatic TS of Cylinder at 7.5 kHz (Line Plot): Kirchhoff vs Burton-Millar BEM

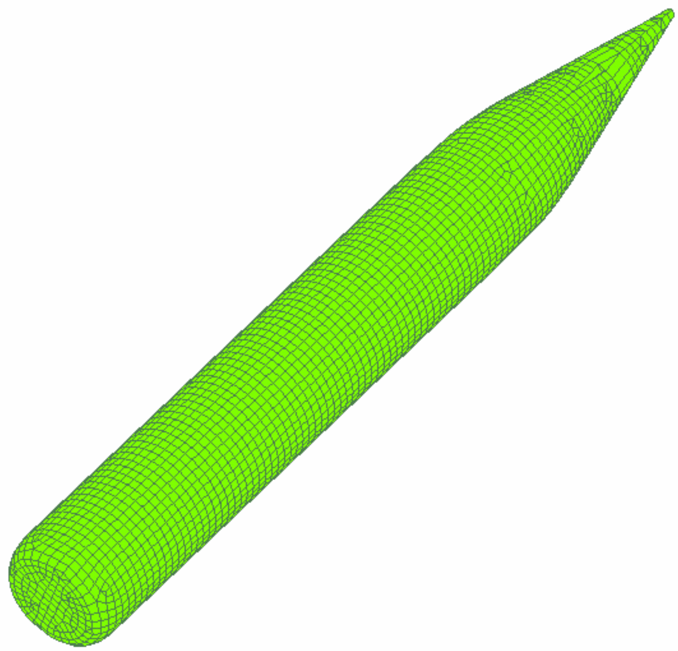

Figure 4.7 AVAST Model of Main Body of Torpedo

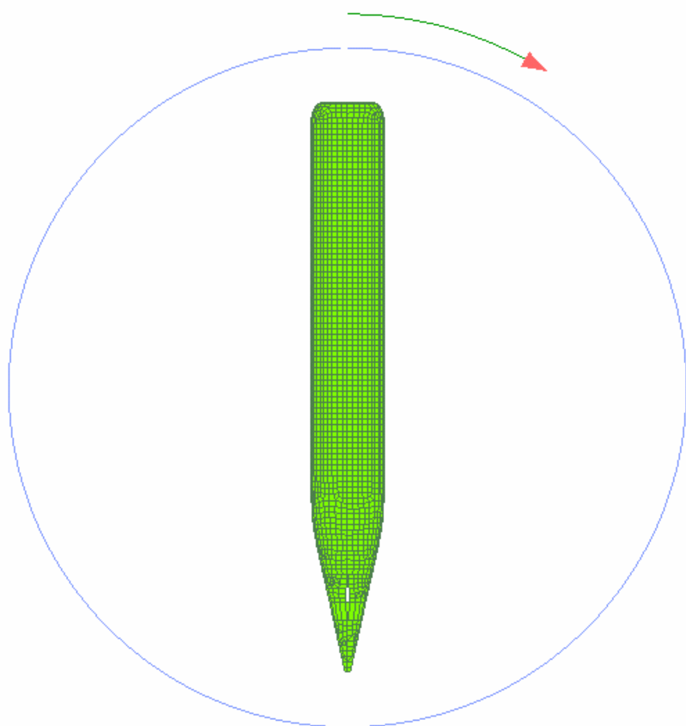

Figure 4.8 Orientation of Torpedo Main Body Field Points

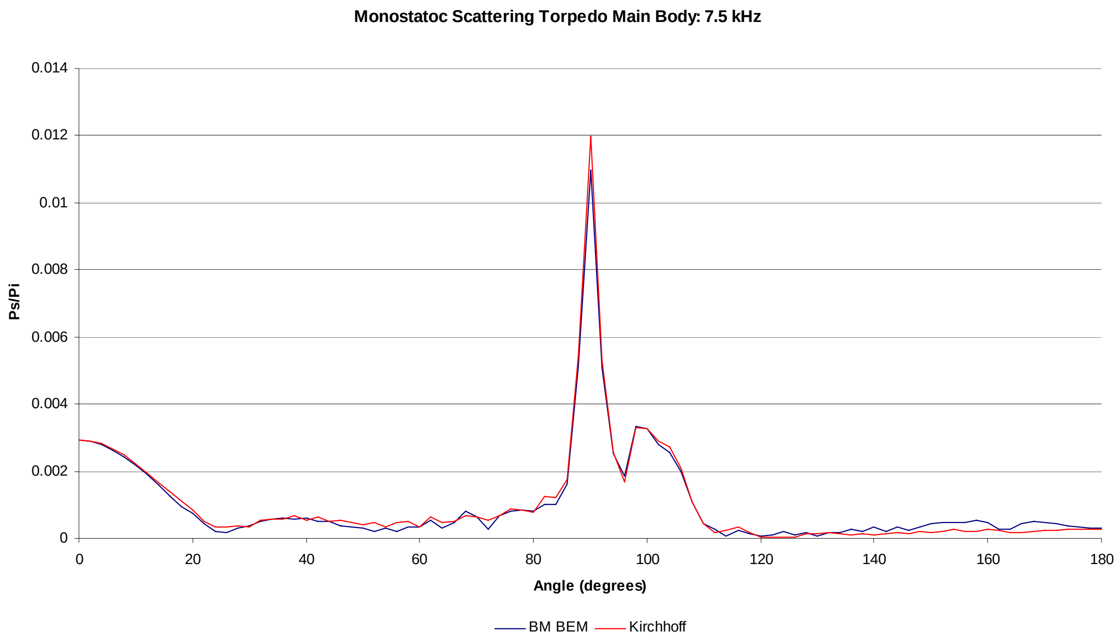

Figure 4.9 Torpedo Main Body Scattered Pressure Results at 7.5 kHz: Kirchhoff vs Conventional BEM

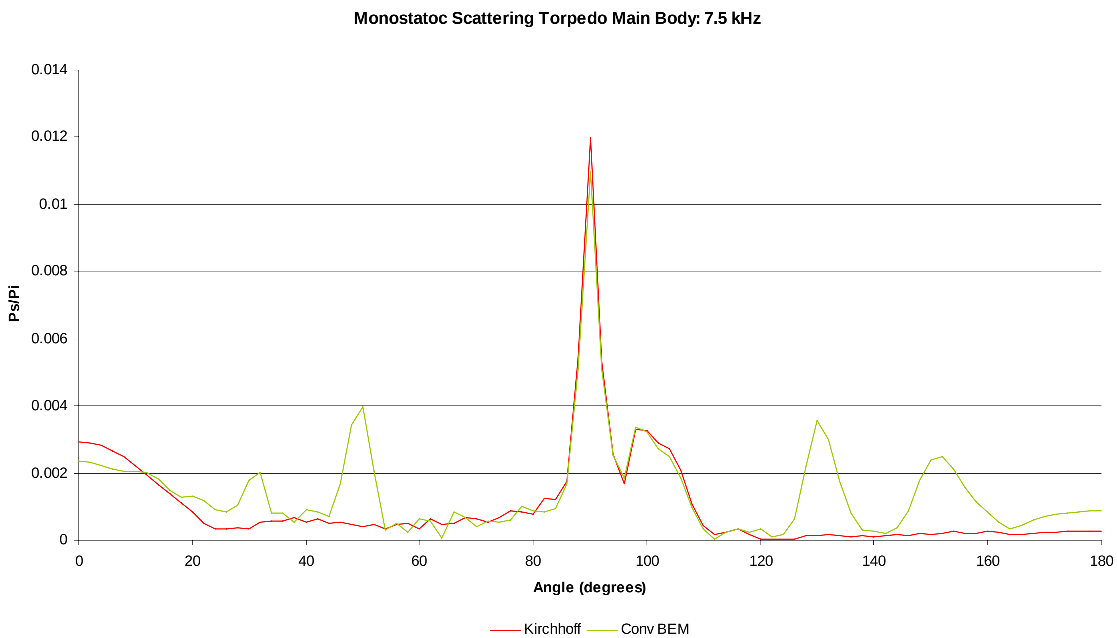

Figure 4.10 Torpedo Main Body Scattered Pressure Results at 7.5 kHz: Kirchhoff vs Burton-Millar BEM

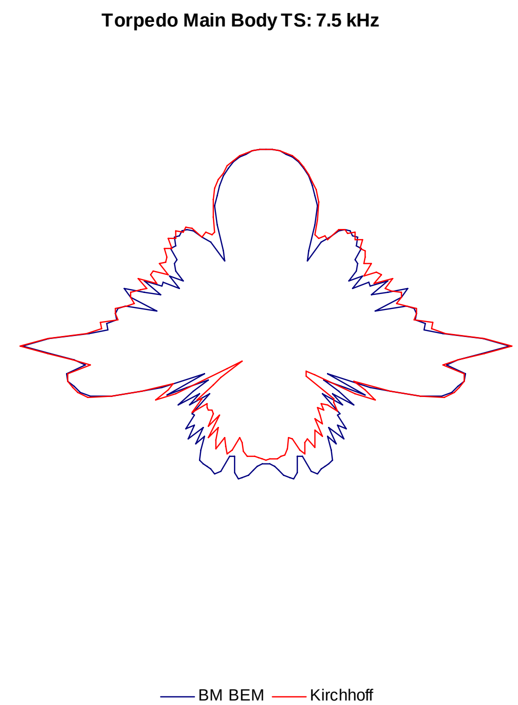

Figure 4.11 Monostatic TS of Torpedo Main Body at 7.5 kHz: Kirchhoff vs Burton-Millar BEM

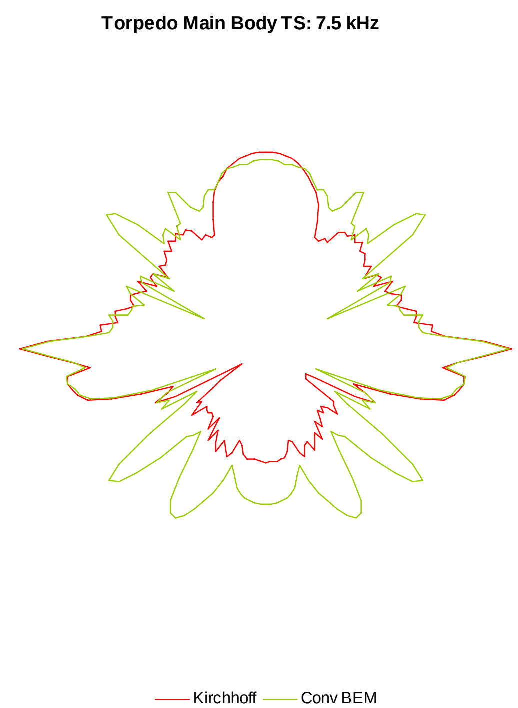

Figure 4.12 Monostatic TS of Torpedo Main Body at 7.5 kHz: Kirchhoff vs

Conventional BEM

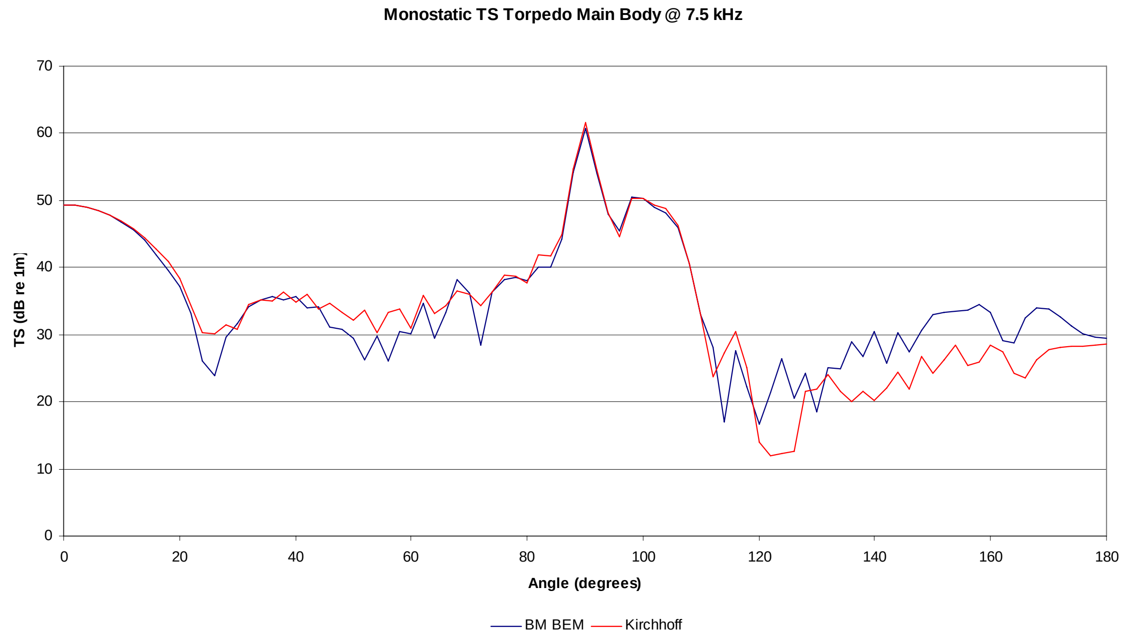

Figure 4.13 Monostatic TS of Torpedo Main Body at 7.5 kHz (180 Degree Sweep): Kirchhoff vs Burton-Millar BEM

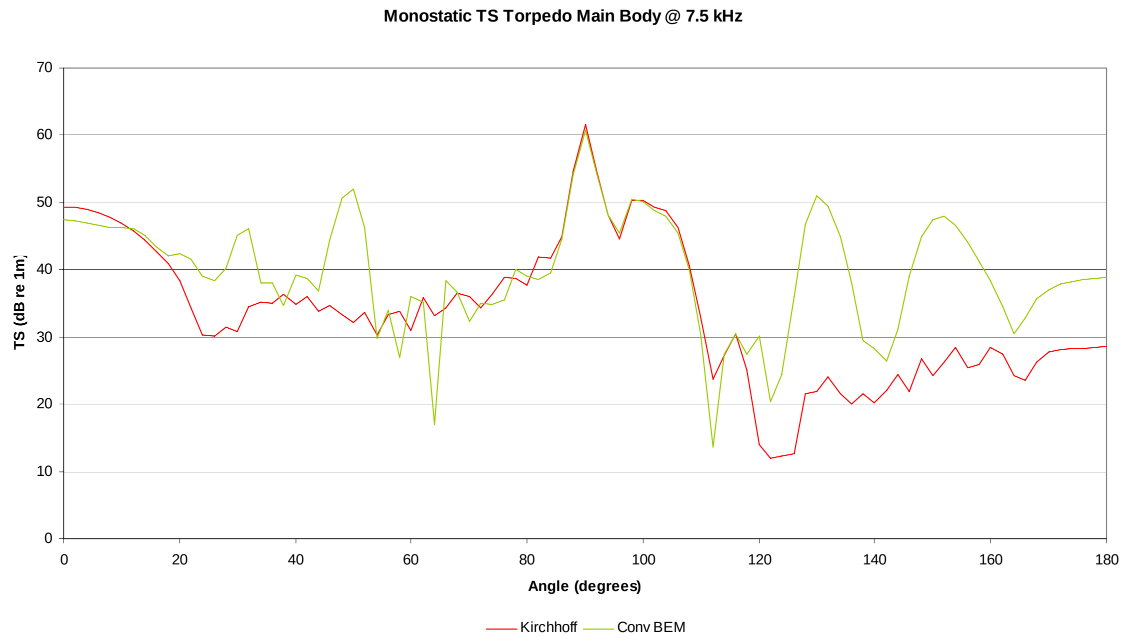

Figure 4.14 Monostatic TS of Torpedo Main Body at 7.5 kHz (180 Degree Sweep): Kirchhoff vs Conventional BEM

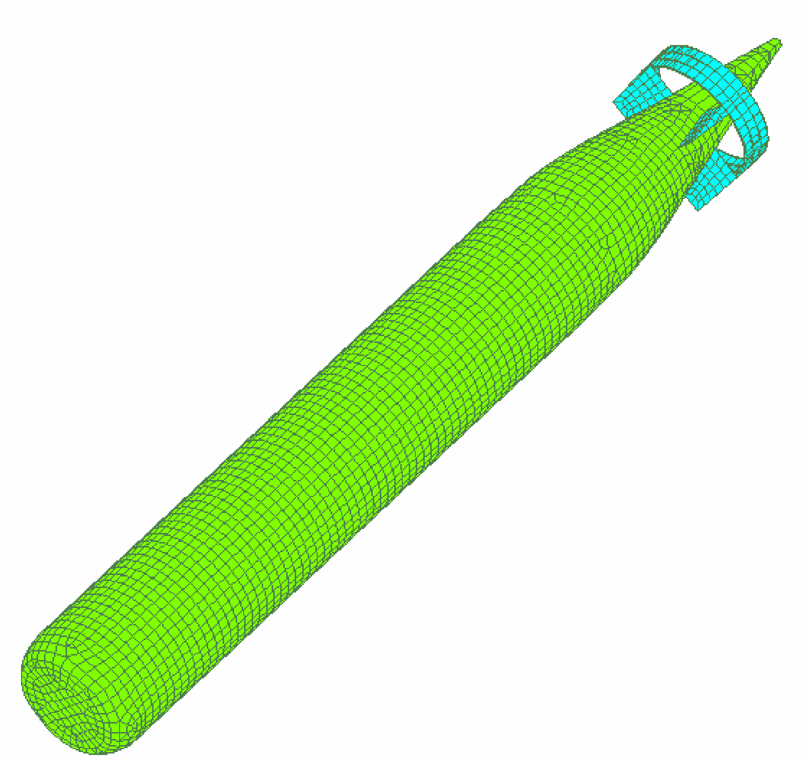

Figure 4.15 AVAST Model of Full Torpedo

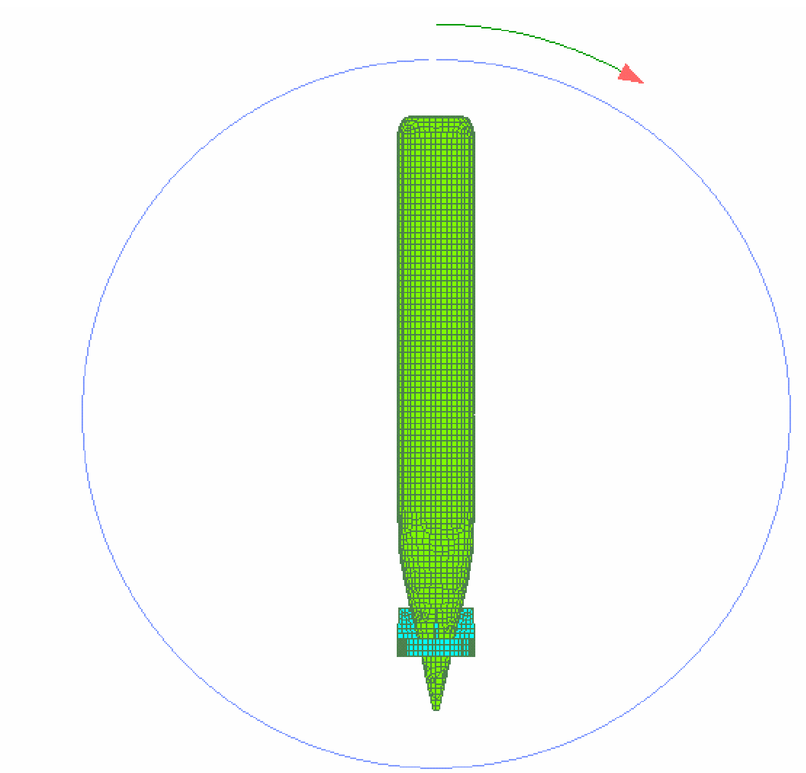

Figure 4.16 Orientation of Full Torpedo Field Points

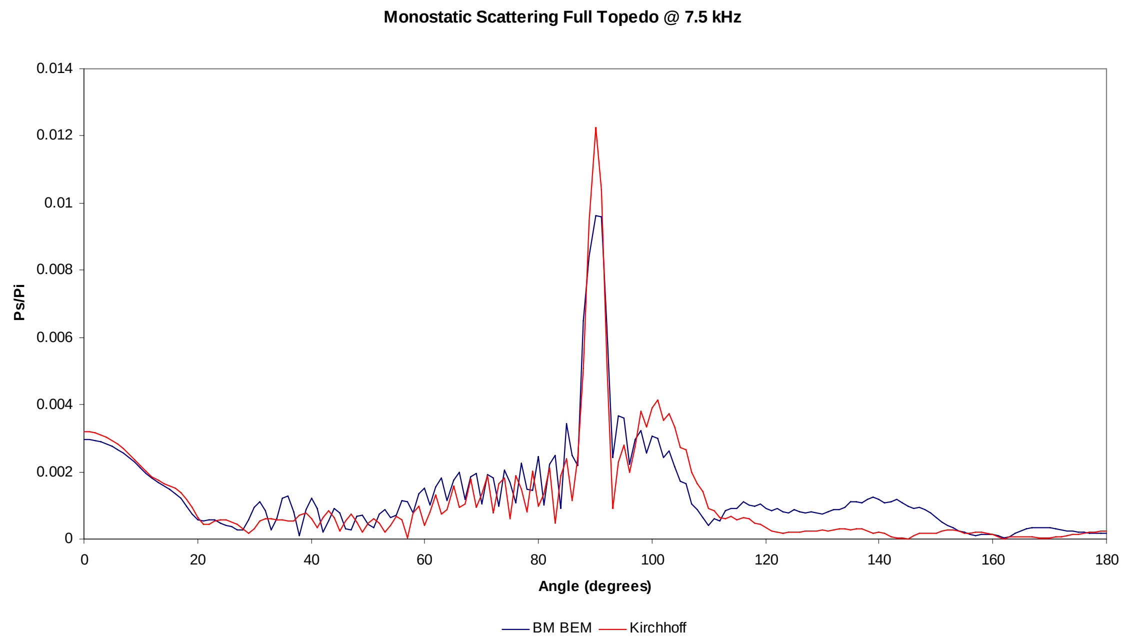

Figure 4.17 Full Torpedo Scattered Pressure Results at 7.5 kHz: Kirchhoff vs Burton-Millar BEM

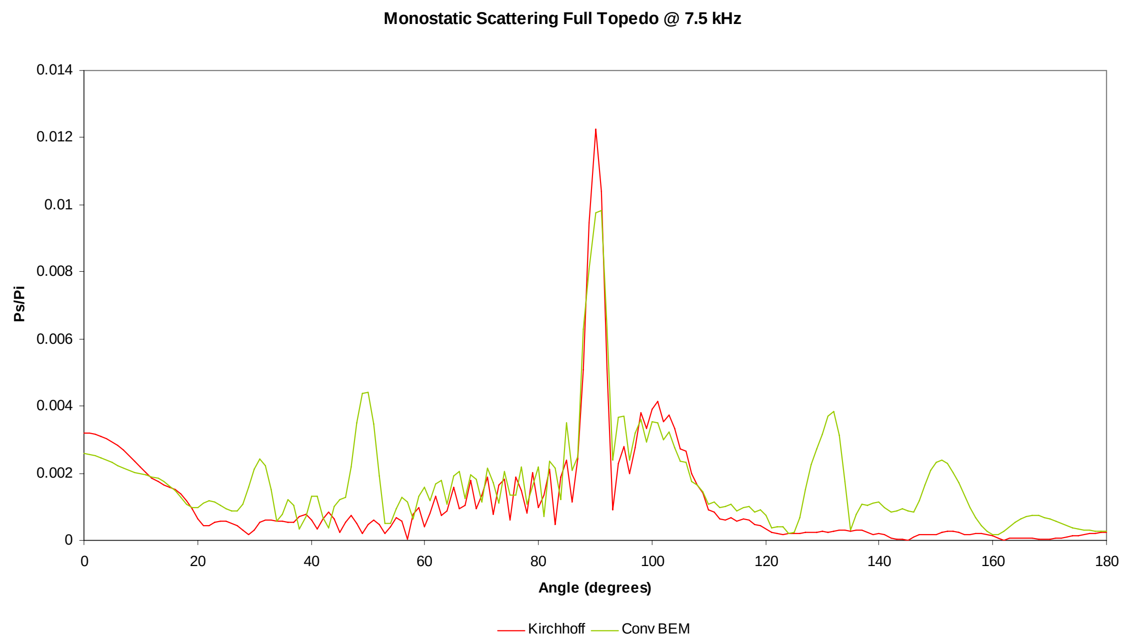

Figure 4.18 Full Torpedo Scattered Pressure Results at 7.5 kHz: Kirchhoff vs Conventional BEM

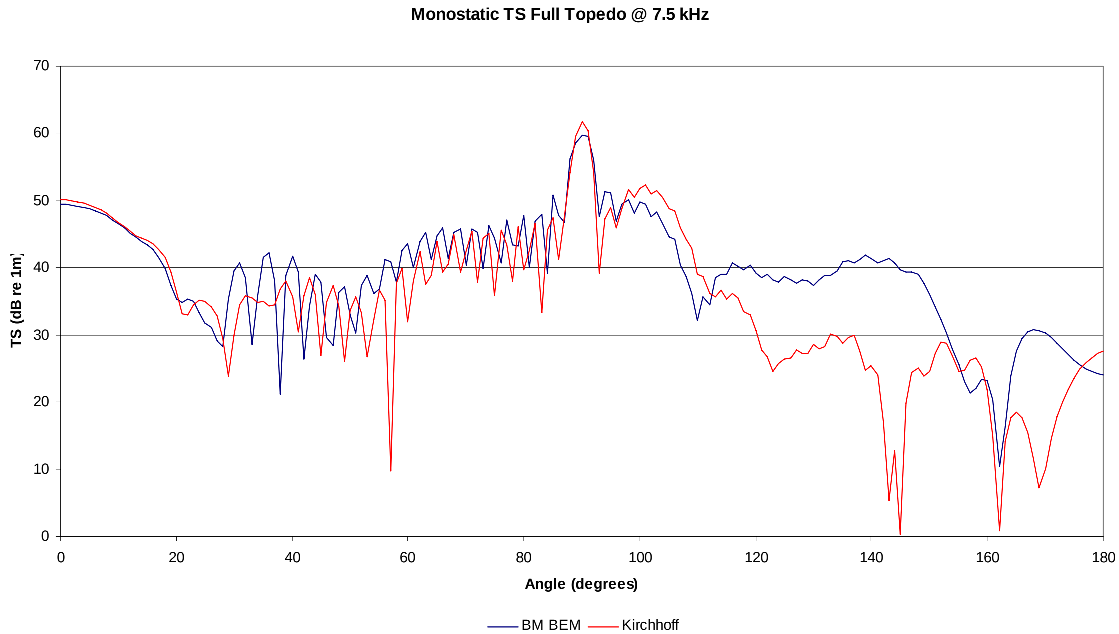

Figure 4.19 Monostatic TS of Full Torpedo at 7.5 kHz: Kirchhoff vs Burton-Millar BEM

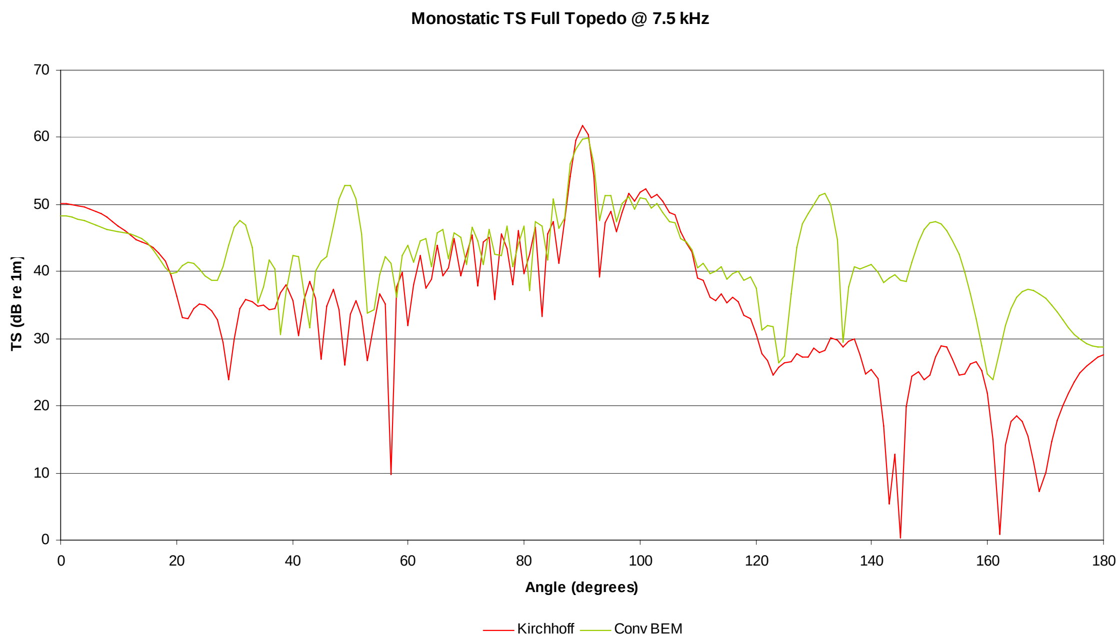

Figure 4.20 Monostatic TS of Full Torpedo at 7.5 kHz: Kirchhoff vs Conventional BEM

5. Develop High-Resolution Models of CF Vessels

The contractor will develop a high-resolution model of the underwater shape of the Canadian Patrol Frigate and CFAV Quest to assist in the development of high frequency target strength models for these vessels. The models should be of sufficient detail to perform target strength predictions at 50 kHz (a wavelength in water of 3 cm). These models should include all underwater appendages such as rudders, bilge keels and propeller shafts and will be as geometrically correct as possible given information currently available for each ship type.

These models require relatively precise descriptions of the submerged hull shape including appendages such as rudders, propellers and shafts. Shape details down to 3 cm in size should be included in the model. In areas where there is little change in shape (i.e. little change in curvature) panel sizes can be larger.

Since the meshing algorithm in AVAST uses lines-of-form to define a smooth hull surface (i.e. no discontinuities in slope), any mesh generated within AVAST is confined to a model of a smooth hull without any appendages. The meshing algorithm also has limitations on the number of lines-of-form that can be used to generate a mesh.

For these reasons, all meshes were generated outside of AVAST and were converted to a format that could be imported into AVAST. All meshes were created through the use of a combination of customized software and general-purpose FEA modelling programs such as HyperMesh and Trident FEA.

5.1 CFAV Quest

The procedure for generating the required meshes started with a precise hull form description in the form of detailed lines-of-form, which were provided by the scientific authority. This was made up of as many as 18 offset points at each of 122 stations. In addition, an FEA model of a single propeller blade, bilge keel data and approximate locations of various appendages were also provided. Since underwater acoustic analyses depend upon the submerged hull surface, the lines-of-form had to be truncated at the waterline. Following consultation with the scientific authority it was decided to use a waterline that is consistent with a deep departure condition, i.e. a displaced weight of 2268.52 tonnes. According to tables provided by DRDC Atlantic, this would produce a draft at midship of 15.659 ft (4.773 m).

The basic hull description of the portside hull surface was modified to include the bossing (fairing) that encases the propeller shaft. The size and shape of this bossing was approximated from rough drawings provided by DRDC Atlantic.

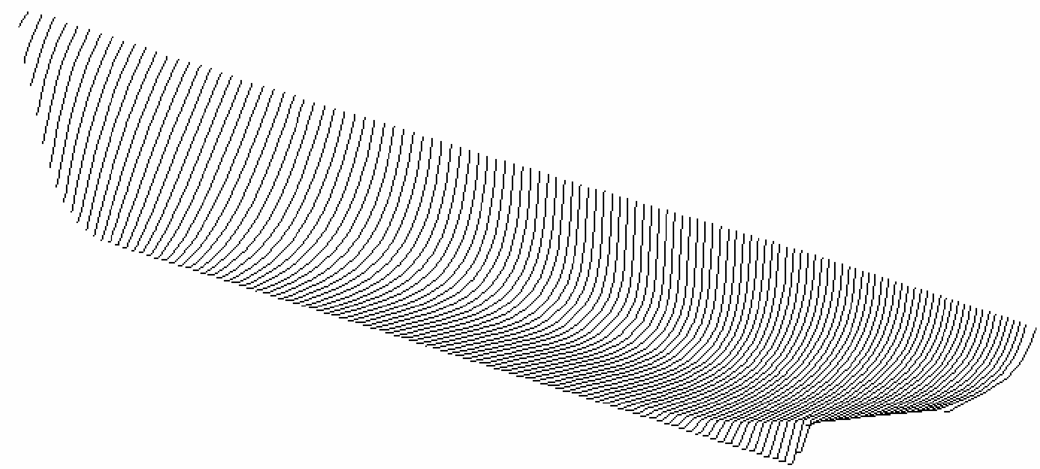

Figure 5.1: Quest lines of form

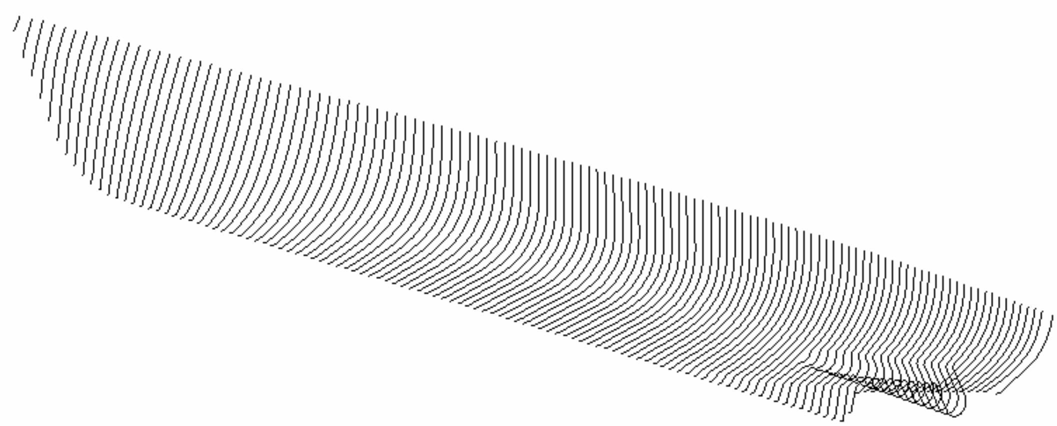

Figure 5.2: Quest lines of form with shaft bossing

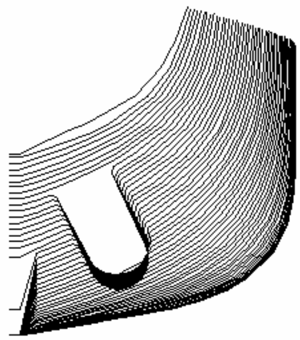

Figure 5.3: Quest lines of form with shaft bossing, longitudinal view

Once the lines-of-form were finished a surface definition of the portside wetted hull surface was generated using a combination of Martec software and third party commercial software. The surface description was modified to include a cutout where the bilge keel was to be inserted. This modified hull surface was then meshed.

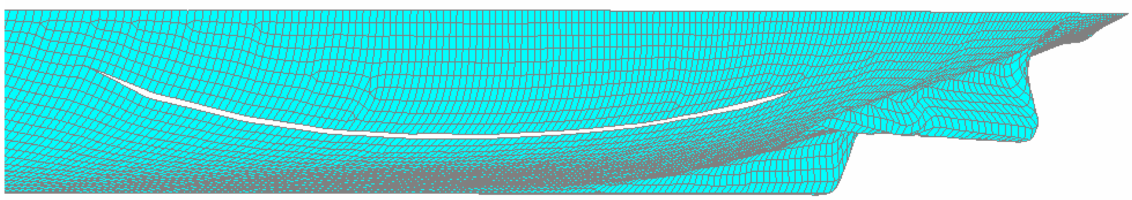

Figure 5.4: Quest hull surface mesh with bilge keel cutout

bilge keel

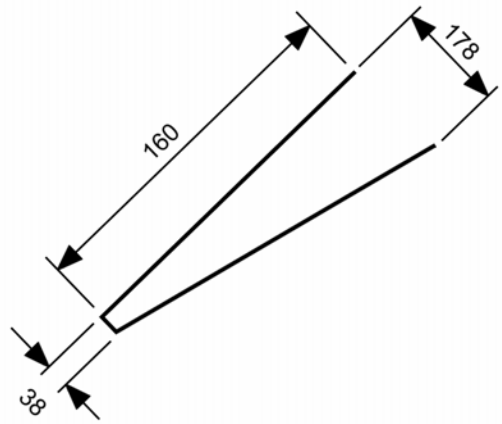

Figure 5.5 Quest bilge keel dimensions

Finally, separate meshes for appendages (rudder and propeller) were added to the hull surface mesh.

The shape of the rudder was approximated from rough drawings provided by DRDC Atlantic. These showed a rudder that is 2743 mm tall, 2483 mm long at the top and 1549 mm long at the bottom. The rudder was assumed to be as wide as 378 mm at the top and as wide as 274 mm wide at the bottom. An elliptical cross section shape was used for the forward portion of the rudder with a straight aft portion that meets the ellipse tangentially.

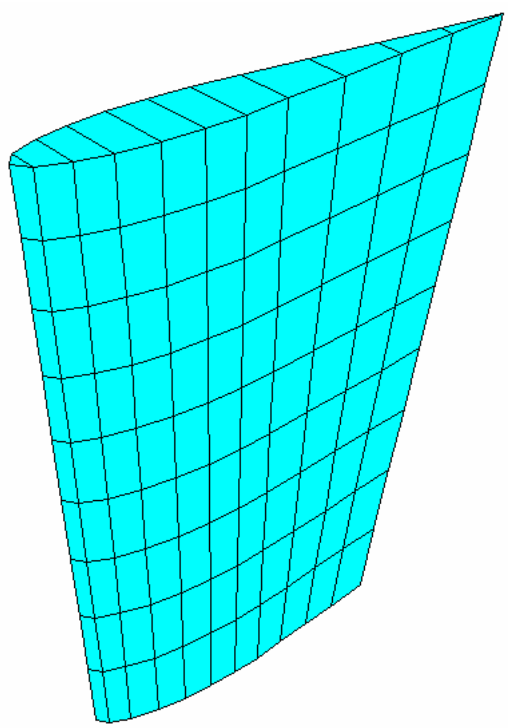

Figure 5.6: Quest coarse rudder mesh (30 cm)

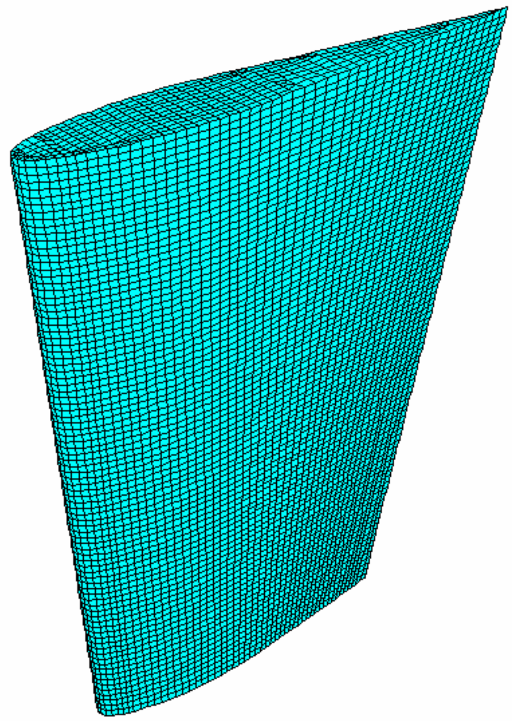

Figure 5.7: Quest fine rudder mesh (3 cm)

The scientific authority provided a finite element model of one Quest propeller blade. A drawing showing the propeller and hub was used as a guide for the description of the hub and the orientation of the blades relative to the hub.

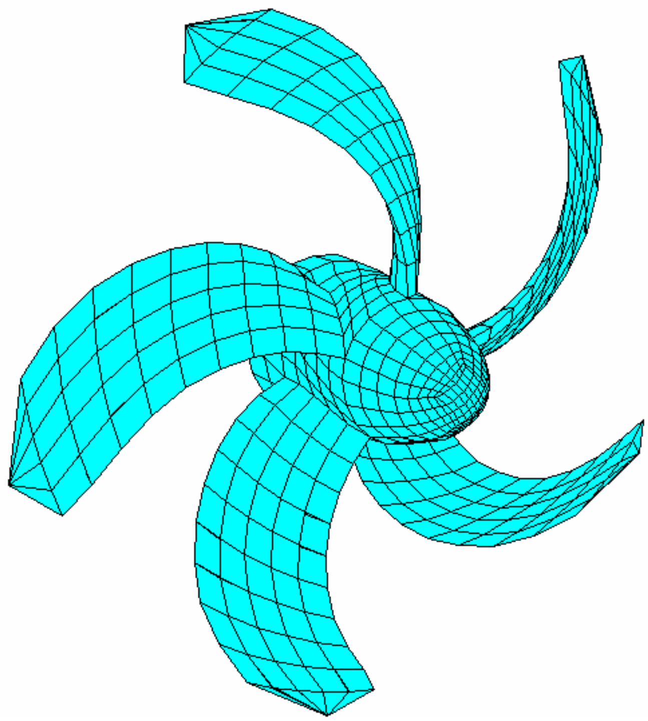

Figure 5.8: Quest coarse propeller mesh (30 cm)

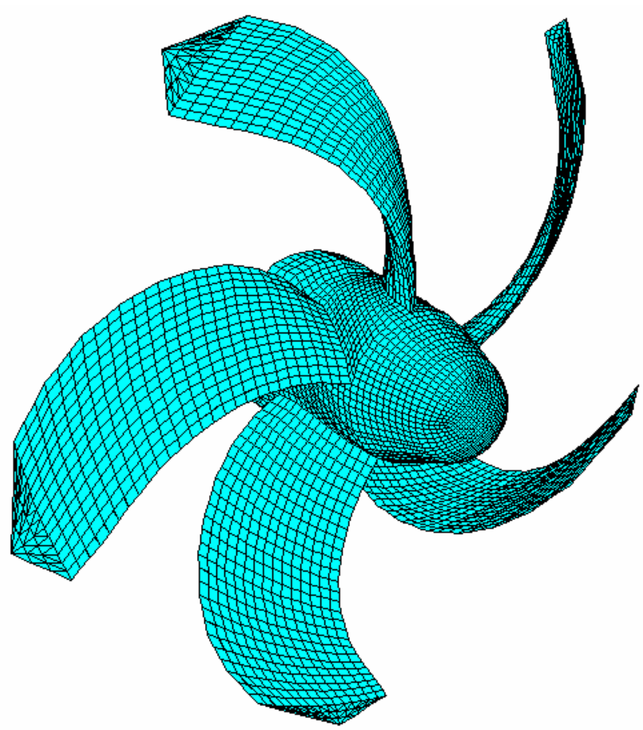

Figure 5.9: Quest fine propeller mesh (3 cm)

Following generation of all appendage meshes, the various meshes were brought together and mirrored about the ship centreline.

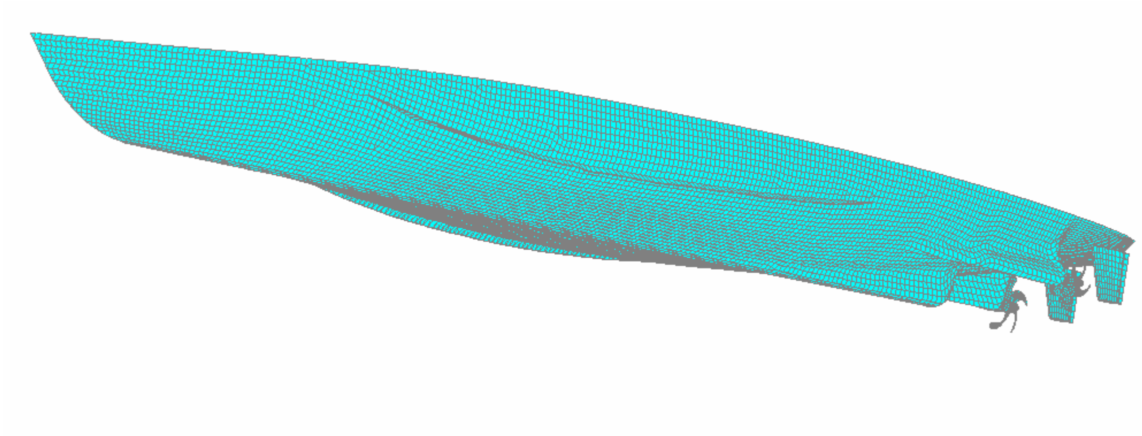

Figure 5.10: Quest complete coarse mesh (30cm)

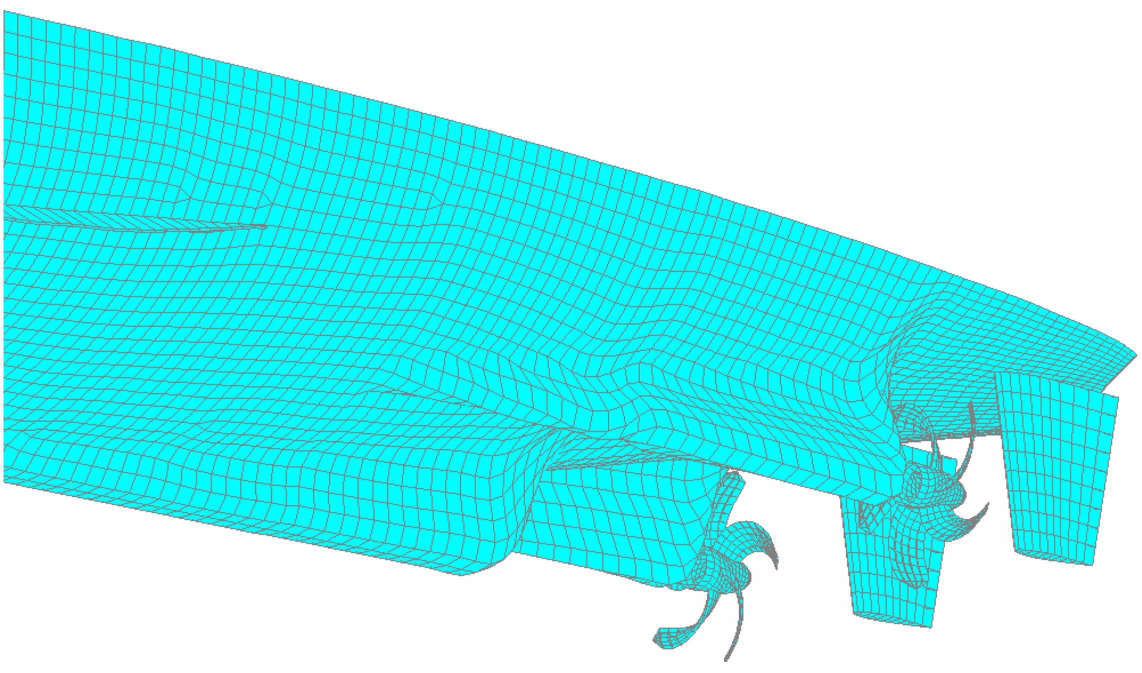

Figure 5.11: Quest complete coarse mesh (close up of stern)

5.2 Canadian Patrol Frigate

Manufacturer's drawings were used to generate highly detailed lines-of-form, as well as geometric descriptions of various appendages (rudder, shaft brackets, bilge keel and sonar dome). As in the case of the Quest model, the scientific authority supplied a finite element mesh of one propeller blade. No information on the propeller hub was available; hence a rather simplified cylindrical approximation was used. Similarly, the shaft was assumed to be a simple cylinder of constant radius equal to the outer radius of the forward shaft bracket hub.

A mesh of the wetted hull surface, with no appendages is shown below. It includes cut-outs for the bilge keels and sonar dome. Panel size is approximately 30 cm and the model contains 22,360 panels.

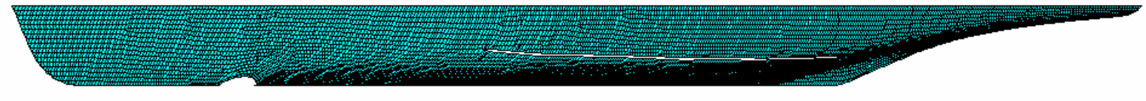

Figure 5.12 CPF Hull Mesh (30 cm mesh size)

The next figure shows a close-up of a portion of the hull showing the cut-outs in a bit more detail.

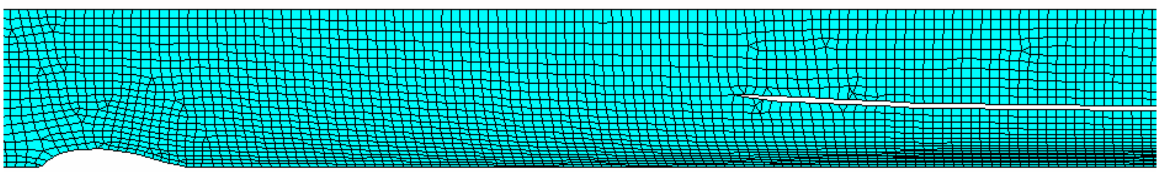

Figure 5.13 CPF Hull Mesh Close up

The bilge keel was modified slightly. On the drawings the bilge keel is shown to consist of upper and lower plates plus a pipe attached to the outer edge of the upper plate. The upper plate extends 150 mm beyond the end of the lower plate. This was approximated by two plates attached at the outboard edge with no pipe. The upper plate extends its full width and the lower plate was extended to mean the end of the upper plate. A portion of the bilge keel mesh is shown in the following figure. Mesh size for the bilge keel, which is relatively flat, is similar to the 30 cm size used on the hull surface.

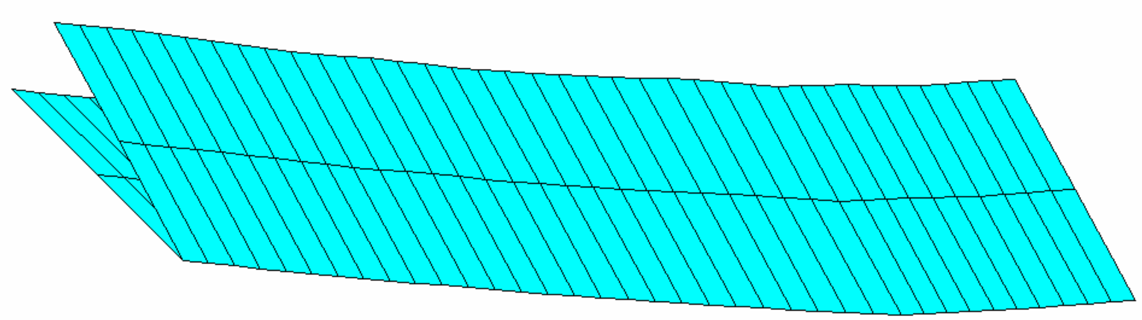

Figure 5.14 Portion of CPF bilge keel mesh

The remaining appendages, including rudders, propellers, shaft brackets, shafts and sonar dome, exhibit higher curvatures than is encountered on the hull surface. Hence finer meshes were used, as can be seen in the following figures. Mesh sizes range from approximately 30 cm to 3 cm.

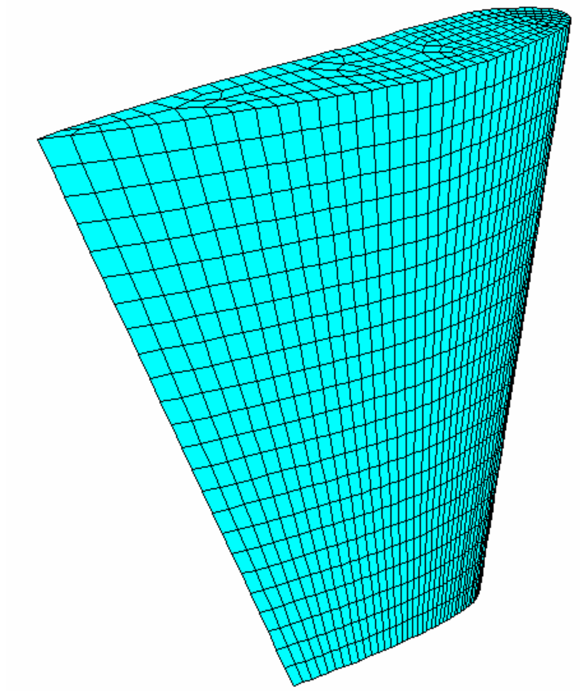

Figure 5.15: CPF rudder mesh

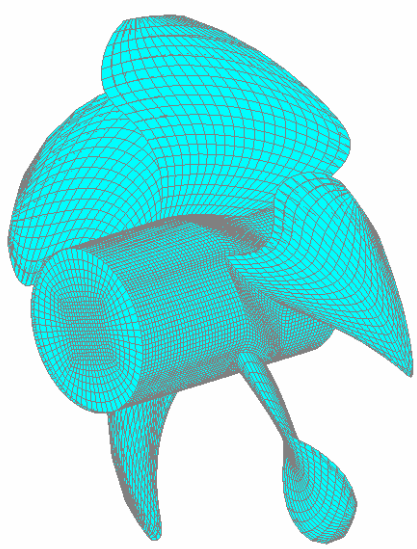

Figure 5.16: CPF propeller mesh (port)

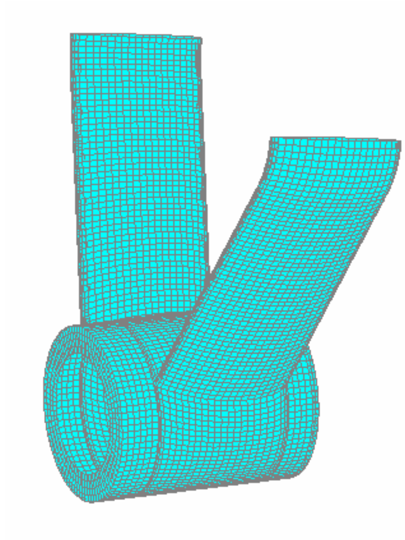

Figure 5.17: CPF forward shaft bracket mesh (port)

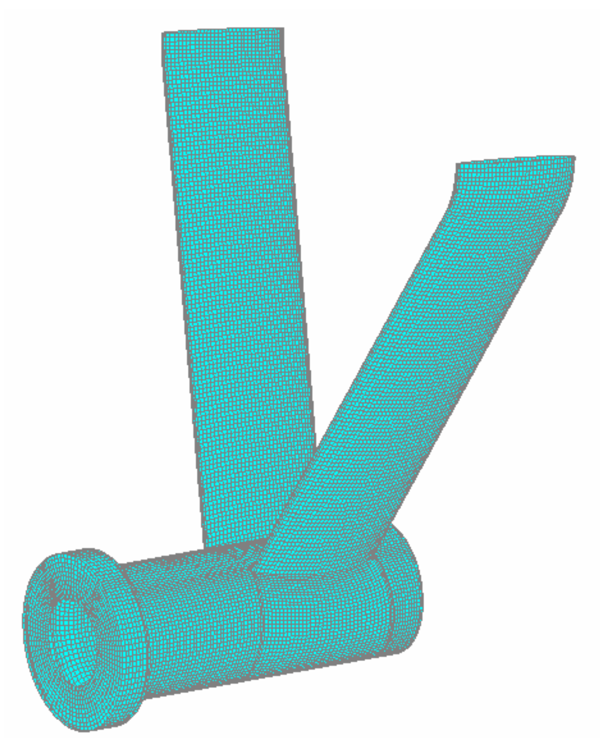

Figure 5.18: CPF aft shaft bracket mesh (port)

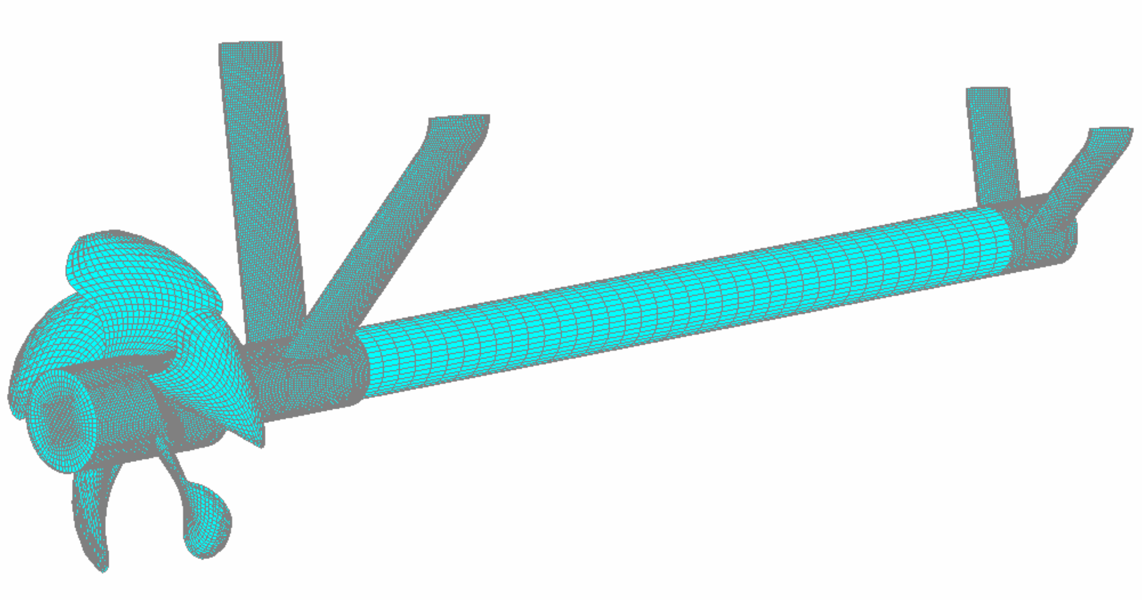

Figure 5.19: CPF shaft mesh, with brackets and propeller (port)

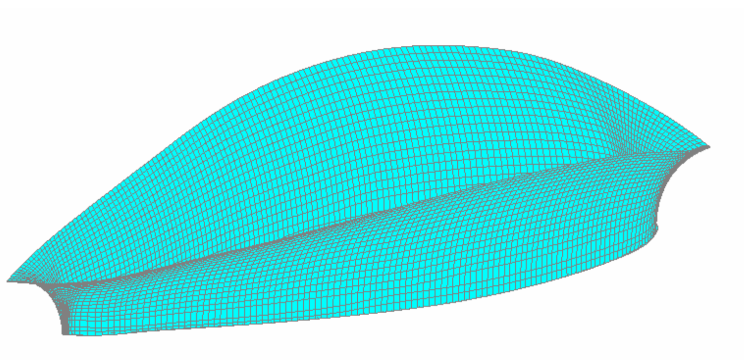

Figure 5.20: CPF sonar dome mesh

When the various appendages are added to the CPF hull surface mesh, the total number of panels on the whole model (no symmetry) is 134,718. This is an extremely large model. Whether or not such a highly refined mesh is required is in question. A convergence study would help to determine the degree of mesh refinement required.

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This report describes the contract addressing the need to extend the current capabilities of DRDC's AVAST software in order to provide a modelling tool suitable for predicting radiated noise and target strength of realistic ship structures. In this work, the contractor developed, as input, high fidelity models of both the Canadian Patrol Frigate and CFAV Quest. For the purpose of acoustic target strength prediction, these models included sufficient detail to allow for predictions at 50 kHz. In terms of radiated noise, the contractor developed a methodology for predicting hull surface accelerations, internal structural vibrations, and internal compartment radiated noise (up to approximately 50 Hz) due to an idealized acoustic source simulating propeller cavitation. The contractor investigated discrepancies between the Kirchhoff and conventional BIEM formulations when used for predicting torpedo target strength. In addition, the contractor provided a capability for including a nominal propeller model when predicting the medium-to-high-frequency target strength of a submarine or torpedo.

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